Household Air Pollution in Ghana: Stove use, health impacts, and policy options

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ABSTRACT

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Background: Three billion individuals worldwide rely on biomass fuel (crops, dung, wood) for cooking and heating, mostly in the developing world. Incomplete combustion of these biomass fuels in inefficient cookstoves leads to high levels of household air pollution (HAP). Health conditions resulting from HAP are responsible for approximately 1.6 million premature deaths each year. Of the diseases associated with HAP exposure, lower respiratory infections (LRIs) are the leading cause of death for children under five worldwide. There is a great need to understand the etiology of HAP-associated LRIs to inform health interventions and to improve treatments. Ultimately, however, the only way to prevent the disease burden from HAP is to stop exposure. Policies and programs to promote the use of clean fuels for cooking are a pivotal prevention strategy.

Methods: All three studies draw from an established cohort in Ghana. The Ghana Randomized Air Pollution and Health Study (GRAPHS), was a cookstove intervention trial in Kintampo, Ghana. Participants were randomized to a more efficient biomass cookstove arm, a liquefied petroleum gas (LPG) stove arm, or the traditional cookstove arm (baseline). The principal outcome of GRAPHS was childhood pneumonia. The first chapter utilizes banked nasal swabs from GRAPHS to assess the relationship between HAP exposures and a panel of known respiratory pathogens. In the second chapter we leverage data on stove use during GRAPHS, and then follow a sub cohort 6 months prior to and 6 months after the GRAPHS termination date. We employ a novel construct, suspended use, to understand the factors associated with people stopping LPG use. The third chapter tests a new randomized intervention on a subset of the GRAPHS participants. We provide free cookstoves, and allocate participants to one of four arms: a behavior change intervention, an intervention where LPG fuel is directly delivered to their home, a dual intervention of behavior change and fuel delivery, or a control arm. We track their stove use to identify the most effective intervention on sustained use.

Results: In Chapter 1, we find that the traditional cookstove users had a higher mean number of microbial species than the LPG (LPG: 2.71, 3-stone: 3.34, $p<0.0001$, $n = 260$). This difference was driven by increased bacterial ($p<0.0001$) rather than viral species presence (non-significant). Adjusted exposure-response analyses, however, produced null results. Chapter 2 identifies several factors associated with reduced or suspended LPG use of intervention cookstoves, including: experience of burns, types of food made, and access to biomass fuels. Finally, in Chapter 3 results show increased use for all three intervention arms, the largest for the direct delivery arm with an increased weekly use of 4.7 minutes per week ($p<0.001$).

Conclusions: Transition away from traditional biomass stoves is projected to curb the health effects of HAP by mitigating exposure, but the full benefits of newer clean cookstove technologies can only be realized if use of these new stoves is absolute and sustained. This work enhances our understanding of the etiology of HAP-associated pneumonia, the drivers of clean cookstove suspension, and informs policies designed to promote clean cookstove sustained use, thus reducing the burden of disease associated with exposure. We recommend future use of the suspended use paradigm in research to

inform future household energy interventions. Additionally, we encourage policymakers to incorporate health behavior change theory and approaches in cookstove intervention and promotion efforts.

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LIST OF ABBREVIATIONS

CBSV	Community-based surveillance volunteer
CO	Carbon monoxide
ELAG	Enhancing LPG Adoption in Ghana
GRAPHS	Ghana Randomized Air Pollution and Health Study
HAP	Household air pollution
H.influenzae	*Haemophilus influenzae*
ITT	Intention-to-treat
KHRC	Kintampo Health Research Centre
LMIC	Low or middle income country
LPG	Liquefied petroleum gas
LRI	Lower respiratory infection
M.catarrhalis	*Moraxella catarrhalis*
PCR	Polymerase chain reaction
PM	Particulate matter
$PM_{2.5}$	Particulate matter of 2.5 micrometers in diameter or less
ppm	Parts per million
RANAS	Risks Attitudes Norms Abilities and Self-Regulation
RCT	Randomized controlled trial
RESPIRE	Randomised Exposure Study of Pollution Indoors and Respiratory Effects
RSV	Respiratory syncytial virus
SES	Socioeconomic status
S.pneumoniae	*Streptococcus pneumoniae*
SUMs	Stove use monitors
TZ	Tuo Zaafi
WTP	Willingness to pay

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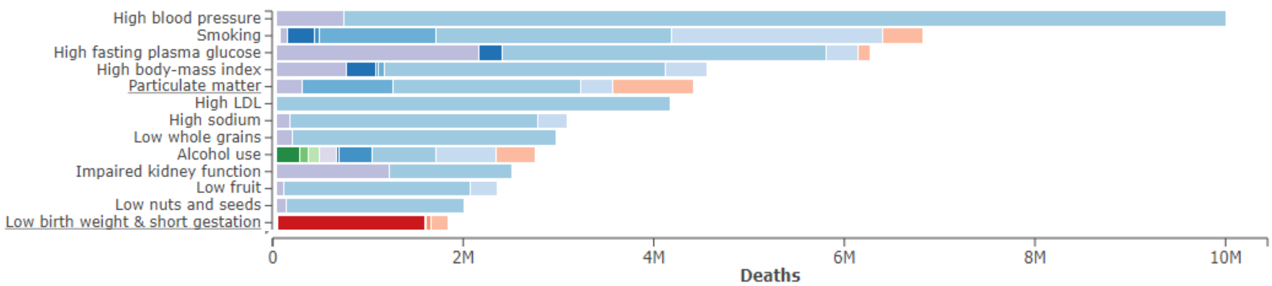
INTRODUCTION

Household air pollution and health

Global burden of air pollution

Poor air quality is one of the largest health concerns worldwide. The Institute for Health Metrics and Evaluation (IMHE) estimates that particulate matter air pollution is the fifth leading cause of preventable deaths in the world, and the leading environmental risk factor (Stanaway et al., 2018a). Air pollution has been linked to health impacts in nearly every bodily system, including the respiratory

Figure 1: Top global modifiable risk factors of premature deaths, 2017. Source: Global burden of disease, 2019.



system, nervous system, and even the reproductive systems, and this body of evidence continues to grow (Hoek et al., 2013; Peterson et al., 2015; Stieb, Chen, Eshoul, & Judek, 2012; Tallon et al., 2017). Sources of air pollution differ by region, and depends on both the organization of human settlements and the mix of pollutants in a particular region (Karagulian et al., 2015). Ambient air pollution refers to complex mixtures of air pollutants experienced outdoors, and from diverse sources. Air pollution researchers and policymakers have historically focused on quantifying and regulating the impact of sources of air pollution in urban contexts, such as vehicle emissions or power plants (Anderson, 2009). Increasingly, researchers recognize the contributions of household air pollution to ambient air pollution (Chafe et al., 2014; Chowdhury et al., 2019; Karagulian et al., 2015; Liu et al., 2016).

Household air pollution

An estimated 3 billion people around the world use biomass fuels as their main source of energy for cooking and/or heating (Bonjour et al., 2013). Combustion of biomass fuels results in a combination of pollutants including fine particles, polycyclic aromatic hydrocarbons, aldehydes, and carbon monoxide (Zhang & Smith, 2003). This mixture is collectively referred to as household air pollution (HAP). In contrast to ambient air pollution, HAP exposures mostly occur in and around the home. The Global Burden of Disease estimated that 1.6 million premature deaths were attributable to HAP exposure in 2017 (Stanaway et al., 2018b). Many diseases have been linked to HAP exposures, but the leading causes of death are thought to arise from cardiovascular diseases (39.1%), acute respiratory infections (27.9%), and chronic obstructive respiratory diseases (15.1%) (Stanaway et al., 2018b).

Lower respiratory infections

Lower respiratory infections (LRIs), namely pneumonia, cause 1.4 million deaths annually among children under five, 95% of which are in low or middle income countries (LMICs) (Sonego, Pellegrin, Becker, & Lazzerini, 2015). This makes LRIs the leading cause of premature death for children under five worldwide, and in LMICs, this disease burden is even more pronounced (McAllister et al., 2019). The etiology of LRIs has been widely studied, and largely attributed to a set of bacterial and viral pathogens. *Streptococcus pneumoniae* caused 44.69 million LRIs globally in 2016, followed by respiratory syncytial virus (10.74 million), *Haemophilus influenzae* (6.08 million) and influenza (5.75 million) (Troeger et al., 2018). Established risk factors for LRIs include exposure to secondhand smoke, malnutrition, HIV/AIDS, other chronic underlying diseases, and exposure to household air pollution (Sonego et al., 2015).

Brief overview of the HAP and LRI literature

Past research has assessed the roles of both ambient and household air pollution on LRI. Ambient observational studies have been conducted in wide geographic contexts, from each continent except for Africa, and meta analyses have shown statistically significant positive associations between $PM_{2.5}$ and LRI incidence (Mehta, Shin, Burnett, North, & Cohen, 2013; Nhung et al., 2017). Observational studies in the context of household air pollution have been conducted on every continent, and have also found significant and positive associations, of seemingly stronger magnitude than the ambient air pollution studies. However, meta analyses specific to HAP exposure were focused particularly on children under 5, which may suggest increased susceptibility of this age group (Bruce, 2008; Po, FitzGerald, & Carlsten, 2011).

LRI has known viral, bacterial, and fungal etiologic pathways, but fungal pathologies are typically only observed in immuno-compromised populations (Rudan, 2008). Infections generally occur when bacteria or viruses colonize or infect the nose and throat, and then migrate into the lower airways wherein infection occurs (Mani & Murray, 2012). The mechanisms behind the air pollution and LRI relationship has been an area of investigation. Several studies suggest that bacterial pneumonias are responsive to air pollution exposure, but not viral pneumonias (O'dempsey et al., 1996; Smith et al., 2011). Mechanistic studies have found that $PM_{2.5}$ may increase the abundance of bacteria in the lower airways, including the genus Streptococcus, which is known to cause pneumonia (Rylance et al., 2016). Additionally, evidence suggests that $PM_{2.5}$ may have one or more effects on macrophages in the lower respiratory tract. It is possible that macrophages simply cannot survive exposure to PM, or the resulting oxidative stress and inflammation (Swiston et al., 2008). Some evidence suggests that PM impairs the macrophages phagocytic response (Zhou & Kobzik, 2007) while other evidence finds uninhibited phagocytosis, but does find impaired oxidative burst (Rylance, Chimpini, et al., 2015). And it is also possible that both impairments are occurring simultaneously (Rylance, Fullerton, et al., 2015). More research is needed to confirm that bacteria are the responsible pathogens of HAP-associated pneumonia and if there is a specific bacterial species, or many. A current gap is the relationship between air pollution and bacteria in the upper airways, which mechanistically precedes LRI. There is little evidence in this area and represents another link in understanding HAP-associated pneumonia (Vanker et al., 2019).

Challenges of intervening on exposure

Given the burden of disease associated with HAP, numerous studies have tried to intervene on exposure. Cookstove intervention trials have taken place worldwide in search of health benefits. From Mexico, Guatemala, Malawi, India, Nepal, and Nigeria, the majority of these studies have demonstrated similar null results (Alexander et al., 2017; Mortimer et al., 2017; Romieu et al., 2009; Smith et al., 2011; Tielsch et al., 2016). These trials share another characteristic: limited exposure reductions (Thomas, Wickramasinghe, Mendis, Roberts, & Foster, 2015). Compounded by a steep and nonlinear dose-response relationship between particulate matter and most health outcomes (Burnett et al., 2014), it is not surprising that researchers have failed to observe health benefits in these studies. Even where near-exclusive use of cleaner stoves has been achieved, reductions in personal exposure have not been as large as hoped (Thomas et al., 2015). This highlights a crucial reality: no household is an island. Exposures come from multiple sources, inside and outside of the home, and cooking choices are made in interdependent social and environmental contexts. In particular, most intervention studies have intervened at the household level, leaving intervention participants exposed to emissions from neighbors' traditional cookstoves. Public health researchers are trying to understand the dynamics of household energy and air pollution in order to achieve meaningful and health-relevant exposure reductions (Ezzati & Baumgartner, 2017).

Socio-ecological determinants of exposure

Energy poverty

Energy poverty is defined as not having the resources to access or use electricity and/or clean cooking fuels (UNDP, 2007). Two principal elements govern household energy use: individual poverty and local availability of clean energies (González-Eguino, 2015; Nussbaumer, Bazilian, & Modi, 2012; Pachauri & Spreng, 2004; Sovacool, 2012). The first component explains individual household dynamics and the share of income that households cannot afford, or choose not to dedicate, to more energy-efficient fuels. The second involves contextual and societal factors that determine the presence and availability of clean fuels in a given location. It is important to understand both of these elements of energy poverty, as they represent separate pathways for intervention. A growing literature focuses on the factors that inform household uptake of clean cookstoves, both initially and over time.

Brief overview of cookstove adoption literature

The scientific literature regarding cookstove adoption has identified numerous conditions associated with new cookstove adoption. These variables are broadly divided into three categories: household/setting characteristics, infrastructure, and knowledge and perceptions (Jeuland, Pattanayak, & Bluffstone, 2015; Lewis & Pattanayak, 2012; E. A. Rehfuess, Puzzolo, Stanistreet, Pope, & Bruce, 2014). Household/setting characteristics are features that describe the household, their neighbors, and/or communities. Examples include ethnicity, religion, maternal and paternal education, female head of household, parental and family wealth/income, household size, and age. While it is consistently true that these variables predict adoption, the direction of the association varies across studies (Lewis & Pattanayak, 2012). The reasons behind these inconsistencies are unexplained, but may represent uncontrolled confounding based on underlying constructs that are contextually relevant, or they may indicate the central role of local conditions in shaping decision processes.

Access-related factors associated with cookstove adoption include 1) financial, tax, and subsidy aspects (2) market development (3) regulation, legislation, and standards, and (4) programmatic and policy mechanisms (Jeuland et al., 2015; Lewis & Pattanayak, 2012; E. A. Rehfuess et al., 2014). Broadly defined, the access factors outline contextual physical and/or organizational facilitators of clean cookstove adoption and sustained use. Fuel access factors are also oftentimes specific to the stove type. For example, improved biomass cookstoves necessitate a different fuel infrastructure than LPG stoves. After an initial stove purchase, some stoves require repeated purchase of fuels. Users are then responsive to the price of the physical stove, but also fuel prices. Considering the fuel access environment of cookstove adoption is imperative for HAP-related interventions.

Understanding knowledge and perceptions preventing behavior change is vital to any health-related intervention. Studies have shown numerous associations with cookstove adoption, including knowledge/perceptions of: the health impacts of HAP, safety benefits of new cookstoves, time-savings benefits, improved cleanliness of newer stoves, social norms, newer cookstove users within a social circle, and the cultural appropriateness of technologies (Lewis & Pattanayak, 2012; E. A. Rehfuess et al., 2014). Generally speaking, knowledge is regarded as highly modifiable whereas attitudes can be more challenging to alter (Kelly & Barker, 2016; Petty & Brinol, 2010). Both elements, however, must be aligned with a new behavior in order to observe behavior change (Mosler, 2012).

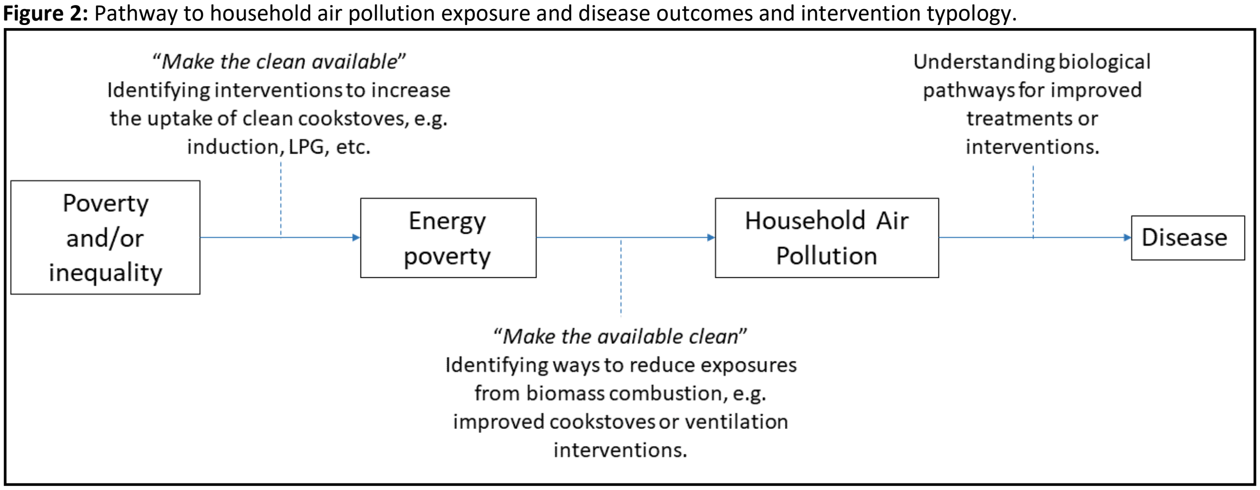
Most cookstove adoption studies have focused on initial adoption versus sustained use. (Lewis & Pattanayak, 2012; Pine et al., 2011). This is an important distinction because adoption studies have largely focused on the enablers and barriers of initial stove acquisition and/or the use of the technology early in its adoption (Ruiz-Mercado, Masera, Zamora, & Smith, 2011). However, there are many reasons to believe that behaviors change over time. For example, researchers have noted situations wherein new stove use is high upon acquisition, but decreases over time. There are plausible reasons why participants would decrease use. New stoves could break with consistent use, and without access or means of repair, participants would likely default to the traditional stove. It is also possible that a household's financial circumstances change and use then falters. Without clear plans to recover from these external stimuli, users would resume traditional stove use. While there is a small number of studies focused on sustained use, that amount is growing. This is because researchers increasingly recognize the importance and complexity of the issue (Global Alliance for Clean Cookstoves, 2015; Gordon & Hyman, 2012; Ruiz-Mercado et al., 2011).

Other reasons to intervene: Climate co-benefits

A number of international initiatives have sought to promote both ecological and human health simultaneously. The World Health Organization has made the promotion of cleaner fuels a priority in its Millennium Development Goals and Sustainable Development Goals (E. Rehfuess, Mehta, & Prüss-Üstün, 2006; Robert, Parris, & Leiserowitz, 2005). The use of firewood or charcoal, for example, involves the harvesting of plant mass which may contribute towards deforestation and, consequently, the removal of carbon sinks (Bailis, Drigo, Ghilardi, & Masera, 2015). Burning collected or purchased solid fuels also releases greenhouse gases, including CO_2, black carbon, methane and N_20 (Smith et al., 2000). Since solid fuels are inefficient combustors, the transition away from solid fuel combustion may also mitigate greenhouse gas emissions (Grieshop, Marshall, & Kandlikar, 2011). Researchers have studied national cookstove transitions and identified net negative radiative forcing associated with reductions in climate-warming aerosol emissions (Huang et al., 2018; Lacey, Henze, Lee, van Donkelaar, & Martin, 2017).

Opportunities to intervene: Pathway to HAP-associated disease

Figure 2: Pathway to household air pollution exposure and disease outcomes and intervention typology.



The ultimate goal of public health research into household energy and HAP is to reduce and eliminate its burden of disease. There are three opportunities to intervene (**Figure 2)**. The first is to *make the clean available*, i.e. increasing access to the cleanest cooking technologies such as LPG, induction, or electric stoves (Smith & Sagar, 2014). To do so, we must understand the relationships between poverty/inequality and energy poverty in order to decouple them. The second opportunity is to *make the available clean*, which relies on creating opportunities to sustain biomass use but decrease HAP production and/or exposure. These interventions are largely technological and engineering-based, such as creating improved cookstoves that increase the efficiency of combustion and reduce emissions. To date, these interventions have largely failed to attain health-based guidelines for exposure reductions and have limited climate benefits (Rosenthal, Quinn, Grieshop, Pillarisetti, & Glass, 2018). Finally, we can interrupt the relationship between exposure and disease. Such interventions require an understanding of HAP-specific disease etiologies. For example, identification of susceptible sub-populations, temporal windows of susceptibility, or other relevant biological processes can provide improved treatments or targeted public health efforts. Our work in Ghana focuses on making the clean available, and understanding HAP-related disease mechanisms.

Research setting: Kintampo, Ghana

This thesis is based on work in Ghana, a lower middle income country located in West Africa with a population of approximately 29 million. Approximately 51% of the population live in rural areas and the per capita gross national income is $1490. The human development index (a composite statistic of life expectancy, education and per capita income indicators, scored from 0 to 1) is 0.579 (WHO, 2018). Kintampo, a district in the Brong-Ahafo region, is the site of this thesis research. It is a predominantly a rural area with a small urban township. The population of Kintampo is projected to be 217,087 in 2019 (Ghana Statistical Service, 2019).

Health Context and the importance of LRI research in Ghana

Since 2000, Ghana has made major strides in reducing the mortality for children under 5, maternal mortality, the burden of HIV/AIDS, and malaria (WHO, 2013). Healthcare access and utilization has also increased, with increasing antenatal care, immunizations, and an improving doctor to population ratio (GHS, 2015; WHO, 2013). The Global Burden of Disease estimates that air pollution is the second highest risk factor for death and disability in Ghana. HAP accounted for 450,000 disability-adjusted life years in 2017 (Stanaway et al., 2018b). The leading causes of death for all age groups are malaria, LRIs, neonatal disorders, ischaemic heart disease, and stroke (Stanaway et al., 2018b). LRIs, heart disease, and stroke are strongly associated with HAP exposures (Smith et al., 2014).

Energy context and importance of cookstove research in Ghana

The United Nations Sustainable Energy for All initiative seeks to ensure universal access to modern energies, to double the rate of improvement in energy efficiency, and to double renewable energy in the global energy mix (Rogelj, McCollum, & Riahi, 2013). These goals aim to sustainably combat energy poverty worldwide. One measure of commitment towards meeting such goals is the establishment of national energy policies. Ghana is one such country with a Sustainable Energy for All national energy policy (Energy-Commission, 2012).

Ghana identified offshore oil and gas reserves in 2007 and began commercial production soon thereafter. The Ghana Gas Company produces LPG as a byproduct of the refining process of natural gas, and LPG is also imported by private entities (Asante et al., 2018). LPG is then sold by 42 LPG marketing companies to gas refilling stations throughout the country. While LPG is increasingly available, biomass fuels are the primary cooking fuels nationwide. LPG is largely available and increasingly used in the capital city, but availability and use in rural areas remains low (Asante et al., 2018; WHO, 2018).

Various components of cookstove adoption and sustained use are contextual in nature. Some examples include: the household/setting characteristics, energy infrastructure, and household knowledge and perceptions. Although cookstove adoption and sustained use has been studied in many contexts, much work remains. Sub-Saharan Africa has the largest proportion of individuals using biomass fuels for cooking, and is the only region globally where traditional biomass use is still growing (IEA, 2016). Sustained use studies are small in number and limited geographically. To our knowledge, there have been few studies in sub-Saharan Africa, which demonstrates a need for continued research in an important region.

Ghana Randomized Air Pollution and Health Study (GRAPHS)

The GRAPHS was a cluster-randomized cookstove intervention trial that took place in Kintampo, Ghana from 2013 to 2016 (Jack et al., 2015). Over 1400 pregnant women were enrolled and randomized to one of three study arms: recipients of an improved biomass stove (BioLite, Brooklyn, NY), recipients of an LPG stove, or a control arm that maintained use of the traditional 3-stone fire. Women in the LPG arm were provided with free LPG fuel over the course of the study. After enrollment, women were tracked over pregnancy, and until the baby reached 1 year of age. The main outcomes of the study were low birthweight and pneumonia in the babies.

Organization of the thesis

This thesis is organized into three chapters. In Chapter 1, we leverage data from the GRAPHS to evaluate the microbial relationship between household air pollution and childhood pneumonia. We first assess whether or not there are differences in viral and/or bacterial carriage based on exposure status. Then we try to identify whether particular microbes drive these relationships. Finally, we conduct exposure-response analyses between carbon monoxide and measures of microbial carriage.

Chapters 2 and 3 focus on household energy dynamics among our study participants. In Chapter 2, we utilize questionnaire data from GRAPHS to understand stove use patterns in the context of free fuel for LPG users. We also enrolled a sub cohort of participants to monitor stove use with sensors during the six months before and after the GRAPHS termination date. After GRAPHS, individuals no longer had free access to LPG. Our goal in Chapter 2 is to understand “suspended use”, a novel construct that emphasizes the importance of understanding the impediments to clean cookstove use, and the reasons why people stop using intervention cookstoves.

Chapter 3 presents the results of the Enhancing LPG Adoption in Ghana (ELAG) study. ELAG was a cluster-randomized sustained use intervention trial whereby we provided participants with LPG stoves, and tested interventions to increase their use over time. We designed two interventions to increase sustained use. The first was a behavioral intervention based on the Risks, Attitudes, Norms, Abilities, and Self-Regulation (RANAS) model. Our second intervention was an access intervention wherein participants received direct, on-demand, delivery of LPG fuel. Deliveries were free to the participant, but the fuel was at their own cost. A third arm of the study was a dual intervention, receiving both the RANAS behavior change and direct delivery of LPG fuels. Our goal for Chapter 3 is to provide policy-relevant information on how to improve cookstove distribution programs in Ghana.

References

Alexander, D., Northcross, A., Wilson, N., Dutta, A., Pandya, R., Ibigbami, T., … Karrison, T. (2017). Randomized controlled ethanol cookstove intervention and blood pressure in pregnant Nigerian women. *American Journal of Respiratory and Critical Care Medicine*, *195*(12), 1629–1639.

Anderson, H. R. (2009). Air pollution and mortality: A history. *Atmospheric Environment*, *43*(1), 142–152. https://doi.org/10.1016/j.atmosenv.2008.09.026

Asante, K. P., Afari-Asiedu, S., Abdulai, M. A., Dalaba, M. A., Carrión, D., Dickinson, K. L., … Jack, D. W. (2018). Ghana's rural liquefied petroleum gas program scale up: A case study. *Energy for Sustainable Development*, *46*, 94–102. https://doi.org/10.1016/j.esd.2018.06.010

Bailis, R., Drigo, R., Ghilardi, A., & Masera, O. (2015). The carbon footprint of traditional woodfuels. *Nature Climate Change*, *5*(3), 266.

Bonjour, S., Adair-Rohani, H., Wolf, J., Bruce, N. G., Mehta, S., Prüss-Ustün, A., … Smith, K. R. (2013). Solid Fuel Use for Household Cooking: Country and Regional Estimates for 1980–2010. *Environmental Health Perspectives*, *121*(7), 784–790. https://doi.org/10.1289/ehp.1205987

Bruce, N. (2008). Indoor air pollution from unprocessed solid fuel use and pneumonia risk in children aged under five years: a systematic review and meta-analysis. *Bulletin of the World Health Organization*, *86*(5), 390–398. https://doi.org/10.2471/BLT.07.044529

Burnett, R. T., Pope, C. A., Ezzati, M., Olives, C., Lim, S. S., Mehta, S., … Cohen, A. (2014). An Integrated Risk Function for Estimating the Global Burden of Disease Attributable to Ambient Fine Particulate Matter Exposure. *Environmental Health Perspectives*, *122*(4), 397–403. https://doi.org/10.1289/ehp.1307049

Chafe, Z. A., Brauer, M., Klimont, Z., Van Dingenen, R., Mehta, S., Rao, S., … Smith, K. R. (2014). Household Cooking with Solid Fuels Contributes to Ambient $PM_{2.5}$ Air Pollution and the Burden of Disease. *Environmental Health Perspectives*, *122*(12), 1314–1320. https://doi.org/10.1289/ehp.1206340

Chowdhury, S., Dey, S., Guttikunda, S., Pillarisetti, A., Smith, K. R., & Di Girolamo, L. (2019). Indian annual ambient air quality standard is achievable by completely mitigating emissions from household sources. *Proceedings of the National Academy of Sciences*, 201900888. https://doi.org/10.1073/pnas.1900888116

Energy-Commission. (2012). *Ghana sustainable energy for all action plan.* Retrieved from http://energycom.gov.gh/files/SE4ALL-GHANA%20ACTION%20PLAN.pdf

Ezzati, M., & Baumgartner, J. C. (2017). Household energy and health: where next for research and practice? *The Lancet*, *389*(10065), 130–132. https://doi.org/10.1016/S0140-6736(16)32506-5

Ghana Statistical Service. (2019). *Projected population by region and sex, 2010, 2015-2020*. Retrieved from http://statsghana.gov.gh/nationalaccount_macros.php?Stats=MTA1NTY1NjgxLjUwNg==/webstats/s679n2sn87

GHS. (2015). *The Health Sector in Ghana: Facts and Figures*. Retrieved from Ghana Health Service website: http://www.moh.gov.gh/wp-content/uploads/2017/07/Facts-and-figures-2015.pdf

Global Alliance for Clean Cookstoves. (2015). *Beyond Distribution: Ensuring and Evaluating the Adoption of Clean Cooking and Its Benefits*. Retrieved from cleancookstoves.org/AdoptionWorkshop

González-Eguino, M. (2015). Energy poverty: An overview. *Renewable and Sustainable Energy Reviews*, *47*, 377–385. https://doi.org/10.1016/j.rser.2015.03.013

Gordon, J., & Hyman, J. (2012). The stoves are also stacked: Evaluating the energy ladder, cookstove swap-out programs and social adoption preferences in the cookstove literature. *Journal of Environmental Investing*, *3*(1), 17.

Grieshop, A. P., Marshall, J. D., & Kandlikar, M. (2011). Health and climate benefits of cookstove replacement options. *Energy Policy*, *39*(12), 7530–7542. https://doi.org/10.1016/j.enpol.2011.03.024

Hoek, G., Krishnan, R. M., Beelen, R., Peters, A., Ostro, B., Brunekreef, B., & Kaufman, J. D. (2013). Long-term air pollution exposure and cardio-respiratory mortality: a review. *Environmental Health*, *12*(1), 43.

Huang, Y., Unger, N., Storelvmo, T., Harper, K., Zheng, Y., & Heyes, C. (2018). Global radiative effects of solid fuel cookstove aerosol emissions. *Atmospheric Chemistry and Physics*, *18*(8), 5219–5233. https://doi.org/10.5194/acp-18-5219-2018

IEA. (2016). *World Energy Outlook 2016*. 684.

Jack, D. W., Asante, K. P., Wylie, B. J., Chillrud, S. N., Whyatt, R. M., Quinn, A. K., … Mujtaba, M. (2015). Ghana randomized air pollution and health study (GRAPHS): study protocol for a randomized controlled trial. *Trials*, *16*(1), 420.

Jeuland, M., Pattanayak, S. K., & Bluffstone, R. (2015). The Economics of Household Air Pollution. *Annual Review of Resource Economics*, *7*(1), 81–108. https://doi.org/10.1146/annurev-resource-100814-125048

Karagulian, F., Belis, C. A., Dora, C. F. C., Prüss-Ustün, A. M., Bonjour, S., Adair-Rohani, H., & Amann, M. (2015). Contributions to cities' ambient particulate matter (PM): A systematic review of local source contributions at global level. *Atmospheric Environment*, *120*, 475–483. https://doi.org/10.1016/j.atmosenv.2015.08.087

Kelly, M. P., & Barker, M. (2016). Why is changing health-related behaviour so difficult? *Public Health*, *136*, 109–116. https://doi.org/10.1016/j.puhe.2016.03.030

Lacey, F. G., Henze, D. K., Lee, C. J., van Donkelaar, A., & Martin, R. V. (2017). Transient climate and ambient health impacts due to national solid fuel cookstove emissions. *Proceedings of the National Academy of Sciences*, *114*(6), 1269–1274. https://doi.org/10.1073/pnas.1612430114

Lewis, J. J., & Pattanayak, S. K. (2012). Who adopts improved fuels and cookstoves? A systematic review. *Environmental Health Perspectives*, *120*(5), 637.

Liu, J., Mauzerall, D. L., Chen, Q., Zhang, Q., Song, Y., Peng, W., … Zhu, T. (2016). Air pollutant emissions from Chinese households: A major and underappreciated ambient pollution source. *Proceedings of the National Academy of Sciences*, *113*(28), 7756–7761. https://doi.org/10.1073/pnas.1604537113

Mani, C. S., & Murray, D. L. (2012). Acute pneumonia and its complications. In *Principles and Practice of Pediatric Infectious Diseases: Fourth Edition*. Elsevier Inc.

McAllister, D. A., Liu, L., Shi, T., Chu, Y., Reed, C., Burrows, J., … Nair, H. (2019). Global, regional, and national estimates of pneumonia morbidity and mortality in children younger than 5 years between 2000 and 2015: a systematic analysis. *The Lancet Global Health*, *7*(1), e47–e57. https://doi.org/10.1016/S2214-109X(18)30408-X

Mehta, S., Shin, H., Burnett, R., North, T., & Cohen, A. J. (2013). Ambient particulate air pollution and acute lower respiratory infections: a systematic review and implications for estimating the global burden of disease. *Air Quality, Atmosphere & Health*, *6*(1), 69–83. https://doi.org/10.1007/s11869-011-0146-3

Mortimer, K., Ndamala, C. B., Naunje, A. W., Malava, J., Katundu, C., Weston, W., … Nyirenda, M. (2017). A cleaner burning biomass-fuelled cookstove intervention to prevent pneumonia in children under 5 years old in rural Malawi (the Cooking and Pneumonia Study): a cluster randomised controlled trial. *The Lancet*, *389*(10065), 167–175.

Mosler, H.-J. (2012). A systematic approach to behavior change interventions for the water and sanitation sector in developing countries: a conceptual model, a review, and a guideline.

International Journal of Environmental Health Research, *22*(5), 431–449. https://doi.org/10.1080/09603123.2011.650156

Nhung, N. T. T., Amini, H., Schindler, C., Kutlar Joss, M., Dien, T. M., Probst-Hensch, N., … Künzli, N. (2017). Short-term association between ambient air pollution and pneumonia in children: A systematic review and meta-analysis of time-series and case-crossover studies. *Environmental Pollution*, *230*, 1000–1008. https://doi.org/10.1016/j.envpol.2017.07.063

Nussbaumer, P., Bazilian, M., & Modi, V. (2012). Measuring energy poverty: Focusing on what matters. *Renewable and Sustainable Energy Reviews*, *16*(1), 231–243. https://doi.org/10.1016/j.rser.2011.07.150

O'dempsey, T. J., Mcardle, T. F., Lloyd-Evans, N., Baldeh, I., Lawrence, B. E., Secka, O., & Greenwood, B. (1996). Pneumococcal disease among children in a rural area of west Africa. *The Pediatric Infectious Disease Journal*, *15*(5), 431–437.

Pachauri, S., & Spreng, D. (2004). Energy Use and Energy Access in Relation to Poverty. *Economic and Political Weekly*, *39*(3), 271–278. Retrieved from JSTOR.

Peterson, B. S., Rauh, V. A., Bansal, R., Hao, X., Toth, Z., Nati, G., … Semanek, D. (2015). Effects of prenatal exposure to air pollutants (polycyclic aromatic hydrocarbons) on the development of brain white matter, cognition, and behavior in later childhood. *JAMA Psychiatry*, *72*(6), 531–540.

Petty, R. E., & Brinol, P. (2010). Attitude change. *Advanced Social Psychology: The State of the Science*, 217–259.

Pine, K., Edwards, R., Masera, O., Schilmann, A., Marrón-Mares, A., & Riojas-Rodríguez, H. (2011). Adoption and use of improved biomass stoves in Rural Mexico. *Energy for Sustainable Development*, *15*(2), 176-183. Available from www.sciencedirect.com/science/article/pii/S0973082611000238. https://doi.org/10.1016/j.esd.2011.04.001

Po, J. Y. T., FitzGerald, J. M., & Carlsten, C. (2011). Respiratory disease associated with solid biomass fuel exposure in rural women and children: systematic review and meta-analysis. *Thorax*, *66*(3), 232–239. https://doi.org/10.1136/thx.2010.147884

Rehfuess, E. A., Puzzolo, E., Stanistreet, D., Pope, D., & Bruce, N. G. (2014). Enablers and barriers to large-scale uptake of improved solid fuel stoves: a systematic review. *Environmental Health Perspectives*, *122*(2), 120–130. https://doi.org/10.1289/ehp.1306639

Rehfuess, E., Mehta, S., & Prüss-Üstün, A. (2006). Assessing household solid fuel use: multiple implications for the Millennium Development Goals. *Environmental Health Perspectives*, *114*(3), 373–378.

Robert, K. W., Parris, T. M., & Leiserowitz, A. A. (2005). What is sustainable development? Goals, indicators, values, and practice. *Environment: Science and Policy for Sustainable Development*, *47*(3), 8–21.

Rogelj, J., McCollum, D. L., & Riahi, K. (2013). The UN's' Sustainable Energy for All'initiative is compatible with a warming limit of 2 C. *Nature Climate Change*, *3*(6), 545.

Romieu, I., Riojas-Rodriguez, H., Marrón-Mares, A. T., Schilmann, A., Perez-Padilla, R., & Masera, O. (2009). Improved biomass stove intervention in rural Mexico: impact on the respiratory health of women. *American Journal of Respiratory and Critical Care Medicine*, *180*(7), 649–656.

Rosenthal, J., Quinn, A., Grieshop, A. P., Pillarisetti, A., & Glass, R. I. (2018). Clean cooking and the SDGs: Integrated analytical approaches to guide energy interventions for health and environment goals. *Energy for Sustainable Development*, *42*, 152–159.

Rudan, I. (2008). Epidemiology and etiology of childhood pneumonia. *Bulletin of the World Health Organization*, *86*(5), 408–416. https://doi.org/10.2471/BLT.07.048769

Ruiz-Mercado, I., Masera, O., Zamora, H., & Smith, K. R. (2011). Adoption and sustained use of improved cookstoves. *Energy Policy*, *39*(12), 7557–7566. https://doi.org/10.1016/j.enpol.2011.03.028

Rylance, J., Chimpini, C., Semple, S., Russell, D. G., Jackson, M. J., Heyderman, R. S., & Gordon, S. B. (2015). Chronic Household Air Pollution Exposure Is Associated with Impaired Alveolar Macrophage Function in Malawian Non-Smokers. *PLOS ONE*, *10*(9), e0138762. https://doi.org/10.1371/journal.pone.0138762

Rylance, J., Fullerton, D. G., Scriven, J., Aljurayyan, A. N., Mzinza, D., Barrett, S., … Gordon, S. B. (2015). Household Air Pollution Causes Dose-Dependent Inflammation and Altered Phagocytosis in Human Macrophages. *American Journal of Respiratory Cell and Molecular Biology*, *52*(5), 584–593. https://doi.org/10.1165/rcmb.2014-0188OC

Rylance, J., Kankwatira, A., Nelson, D. E., Toh, E., Day, R. B., Lin, H., … Gordon, S. B. (2016). Household air pollution and the lung microbiome of healthy adults in Malawi: a cross-sectional study. *BMC Microbiology*, *16*(1). https://doi.org/10.1186/s12866-016-0803-7

Smith, K. R., Bruce, N., Balakrishnan, K., Adair-Rohani, H., Balmes, J., Chafe, Z., … Rehfuess, E. (2014). Millions Dead: How Do We Know and What Does It Mean? Methods Used in the Comparative

Risk Assessment of Household Air Pollution. *Annual Review of Public Health*, *35*(1), 185–206. https://doi.org/10.1146/annurev-publhealth-032013-182356

Smith, K. R., McCracken, J. P., Weber, M. W., Hubbard, A., Jenny, A., Thompson, L. M., … Bruce, N. (2011). Effect of reduction in household air pollution on childhood pneumonia in Guatemala (RESPIRE): a randomised controlled trial. *The Lancet*, *378*(9804), 1717–1726. https://doi.org/10.1016/S0140-6736(11)60921-5

Smith, K. R., & Sagar, A. (2014). Making the clean available: escaping India's Chulha Trap. *Energy Policy*, *75*, 410–414.

Smith, K. R., Uma, R., Kishore, V., Zhang, J., Joshi, V., & Khalil, M. (2000). Greenhouse implications of household stoves: an analysis for India. *Annual Review of Energy and the Environment*, *25*(1), 741–763.

Sonego, M., Pellegrin, M. C., Becker, G., & Lazzerini, M. (2015). Risk Factors for Mortality from Acute Lower Respiratory Infections (ALRI) in Children under Five Years of Age in Low and Middle-Income Countries: A Systematic Review and Meta-Analysis of Observational Studies. *PLOS ONE*, *10*(1), e0116380. https://doi.org/10.1371/journal.pone.0116380

Sovacool, B. K. (2012). The political economy of energy poverty: A review of key challenges. *Energy for Sustainable Development*, *16*(3), 272–282. https://doi.org/10.1016/j.esd.2012.05.006

Stanaway, J. D., Afshin, A., Gakidou, E., Lim, S. S., Abate, D., Abate, K. H., … Murray, C. J. L. (2018a). Global, regional, and national comparative risk assessment of 84 behavioural, environmental and occupational, and metabolic risks or clusters of risks for 195 countries and territories, 1990–2017: a systematic analysis for the Global Burden of Disease Study 2017. *The Lancet*, *392*(10159), 1923–1994. https://doi.org/10.1016/S0140-6736(18)32225-6

Stanaway, J. D., Afshin, A., Gakidou, E., Lim, S. S., Abate, D., Abate, K. H., … Murray, C. J. L. (2018b). Global, regional, and national comparative risk assessment of 84 behavioural, environmental and occupational, and metabolic risks or clusters of risks for 195 countries and territories, 1990–2017: a systematic analysis for the Global Burden of Disease Study 2017. *The Lancet*, *392*(10159), 1923–1994. https://doi.org/10.1016/S0140-6736(18)32225-6

Stieb, D. M., Chen, L., Eshoul, M., & Judek, S. (2012). Ambient air pollution, birth weight and preterm birth: a systematic review and meta-analysis. *Environmental Research*, *117*, 100–111.

Swiston, J. R., Davidson, W., Attridge, S., Li, G. T., Brauer, M., & van Eeden, S. F. (2008). Wood smoke exposure induces a pulmonary and systemic inflammatory response in firefighters. *European Respiratory Journal*, *32*(1), 129–138. https://doi.org/10.1183/09031936.00097707

Tallon, L. A., Manjourides, J., Pun, V. C., Mittleman, M. A., Kioumourtzoglou, M.-A., Coull, B., & Suh, H. (2017). Erectile dysfunction and exposure to ambient Air pollution in a nationally representative cohort of older Men. *Environmental Health*, *16*(1), 12.

Thomas, E., Wickramasinghe, K., Mendis, S., Roberts, N., & Foster, C. (2015). Improved stove interventions to reduce household air pollution in low and middle income countries: a descriptive systematic review. *BMC Public Health*, *15*(1), 650. https://doi.org/10.1186/s12889-015-2024-7

Tielsch, J. M., Katz, J., Khatry, S. K., Shrestha, L., Breysse, P., Zeger, S., … LeClerq, S. C. (2016). Effect of an improved biomass stove on acute lower respiratory infections in young children in rural Nepal: a cluster-randomised, step-wedge trial. *The Lancet Global Health*, *4*, S19.

Troeger, C., Blacker, B., Khalil, I. A., Rao, P. C., Cao, J., Zimsen, S. R. M., … Reiner, R. C. (2018). Estimates of the global, regional, and national morbidity, mortality, and aetiologies of lower respiratory infections in 195 countries, 1990–2016: a systematic analysis for the Global Burden of Disease Study 2016. *The Lancet Infectious Diseases*, *18*(11), 1191–1210. https://doi.org/10.1016/S1473-3099(18)30310-4

UNDP. (2007). *Energizing Poverty Reduction: A Review of the Energy-Poverty Nexus in Poverty Reduction Strategy Papers*. Retrieved from United Nations Development Program website: https://www.undp.org/content/undp/en/home/librarypage/environment-energy/sustainable_energy/energizing_povertyreductionareviewoftheenergy-povertynexusinprsp.html

Vanker, A., Nduru, P. M., Barnett, W., Dube, F. S., Sly, P. D., Gie, R. P., … Zar, H. J. (2019). Indoor air pollution and tobacco smoke exposure: impact on nasopharyngeal bacterial carriage in mothers and infants in an African birth cohort study. *ERJ Open Research*, *5*(1), 00052–02018.

WHO. (2013). *Ghana: WHO statistical profile*. Retrieved from https://www.who.int/gho/countries/gha.pdf?ua=1

WHO. (2018). *Opportunities for transition to clean household energy: application of the Household Energy Assessment Rapid Tool (HEART) in Ghana*. Retrieved from https://www.who.int/airpollution/publications/transition-to-clean-household-energy-Ghana/en/

Zhang, J. (Jim), & Smith, K. R. (2003). Indoor air pollution: a global health concern. *British Medical Bulletin*, *68*(1), 209–225. https://doi.org/10.1093/bmb/ldg029

Zhou, H., & Kobzik, L. (2007). Effect of Concentrated Ambient Particles on Macrophage Phagocytosis and Killing of Streptococcus pneumoniae. *American Journal of Respiratory Cell and Molecular Biology*, *36*(4), 460–465. https://doi.org/10.1165/rcmb.2006-0293OC

CHAPTER 1

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Title: Examining the relationship between household air pollution and infant microbial nasal carriage in a Ghanaian cohort

Abstract:

Background: Pneumonia, a leading cause of childhood mortality, is associated with household air pollution (HAP) exposure. Mechanisms between HAP and pneumonia are poorly understood, but studies show HAP-associated pneumonia is likely of bacterial etiology. We assessed the relationship between HAP and infant microbial nasal carriage among 260 infants participating in the Ghana Randomized Air Pollution and Health Study (GRAPHS).

Methods: The data are from GRAPHS, a cluster-randomized controlled trial of cookstove interventions (improved biomass or LPG) versus the 3-stone (baseline) cookstove. Infants were surveilled for pneumonia during the first year of life and had routine personal exposure assessments. Nasopharyngeal swabs collected from pneumonia cases (n=130) and healthy controls (n=130) were analysed for presence of 22 common respiratory microbes by MassTag polymerase chain reaction. Data analyses included intention-to-treat (ITT) comparisons of microbial species presence by study arm, and exposure-response relationships.

Results: In ITT analyses, 3-stone arm participants had a higher mean number of microbial species than the LPG (LPG: 2.71, 3-stone: 3.34, $p<0.0001$, $n = 260$). This difference was driven by increased bacterial ($p<0.0001$) rather than viral species presence (non-significant). Results were pronounced in pneumonia cases and attenuated in healthy controls. Higher prevalence bacterial species were *Haemophilus influenzae*, *Streptococcus pneumoniae*, and *Moraxella catarrhalis*. Bonferroni-adjusted exposure-response analyses, however, produced null results.

Conclusions: Our intention-to-treat findings are consistent with a link between HAP and bacterial nasal carriage. No relationships were found for viral carriage.

Introduction:

Approximately 3 billion people worldwide use biomass fuels for their cooking and heating needs, including wood, dung, charcoal, and crop residues (Bonjour et al., 2013). The combustion of these fuels produces a complex mixture of air pollutants collectively termed household air pollution (HAP). These air pollutants contributed to 59 million disability-adjusted life years and 1.6 million premature deaths worldwide in 2017 (Institute for Health Metrics and Evaluation, 2017). Of the diseases HAP contributes to, pneumonia has the largest impact on children (Gordon et al., 2014; Smith et al., 2014). Pneumonia is the leading cause of infectious disease mortality worldwide for children under five years of age (World Health Organization, 2016), and almost half of that mortality is in Sub-Saharan Africa (Troeger et al., 2017). In Ghana, where our study is based, pneumonia is the second leading cause of death for children under five, causing over 6,000 deaths in 2016 (Troeger et al., 2017; UNICEF, 2018).

There is strong evidence to support a link between air pollution and respiratory infections like pneumonia (Brauer et al., 2002; MacIntyre et al., 2014; Romieu, Samet, Smith, & Bruce, 2002; Troeger et al., 2017). A number of HAP-specific studies have found such an association (Dherani et al., 2008; Smith, 2000). However, evidence from randomized-controlled trials (RCTs) has been inconsistent (Mortimer et al., 2017). Intention-to-treat results for RESPIRE in Guatemala yielded inconclusive results for pneumonia, but severe pneumonia showed significant results. Exposure-response analyses in RESPIRE, however, did find a significant relationship with pneumonia (Smith et al., 2011). A small subset of air pollution epidemiology studies has specifically investigated the etiology of HAP-associated pneumonia. Several studies suggest that air pollution exposure increases risk of bacterial pneumonias, but not viral pneumonias (Rylance et al., 2015; Smith et al., 2011; Zhou & Kobzik, 2007). The RESPIRE study, for example, found a decrease in respiratory syncytial virus negative (RSV-) pneumonia with lower levels of HAP exposure, but no impact on RSV+ infections. Studies in the Gambia and Malawi have shown similar relationships (Weber et al., 1999).

Pneumonia incidence has been on the decline worldwide, which has been attributed both to increased uptake of the pneumococcal conjugate vaccine, and also to improved nutrition (Rudan, 2008; Walker et al., 2013). Ghana has been particularly successful in its national childhood vaccination efforts, especially in rural areas (Asuman, Ackah, & Enemark, 2018). In our Ghana cohort, we have found that 91.4% of our rural participants received the three scheduled pneumococcal vaccines by the child's first birthday. This high background level of vaccination affords the opportunity to isolate and investigate the role of HAP, rather than secular trends of increasing vaccination access, on pneumonia.

Leveraging the Ghana Randomized Air Pollution and Health Study (GRAPHS), we examined patterns of infant nasal microbial carriage in relation to HAP exposure (Jack et al., 2015). We focus on understanding the role of HAP and particular microbial agents known to cause pneumonia in clinician-diagnosed cases and healthy controls. We hypothesized that: 1) High and low HAP exposure groups will have similar viral carriage patterns, and (2) the high HAP exposure group will have higher bacterial carriage compared to the low exposure group. We then conducted exposure-response analyses to assess relationships between pre and postnatal HAP exposure on 1) species-specific bacterial carriage, and 2) carriage of one or multiple bacterial species.

Methods:

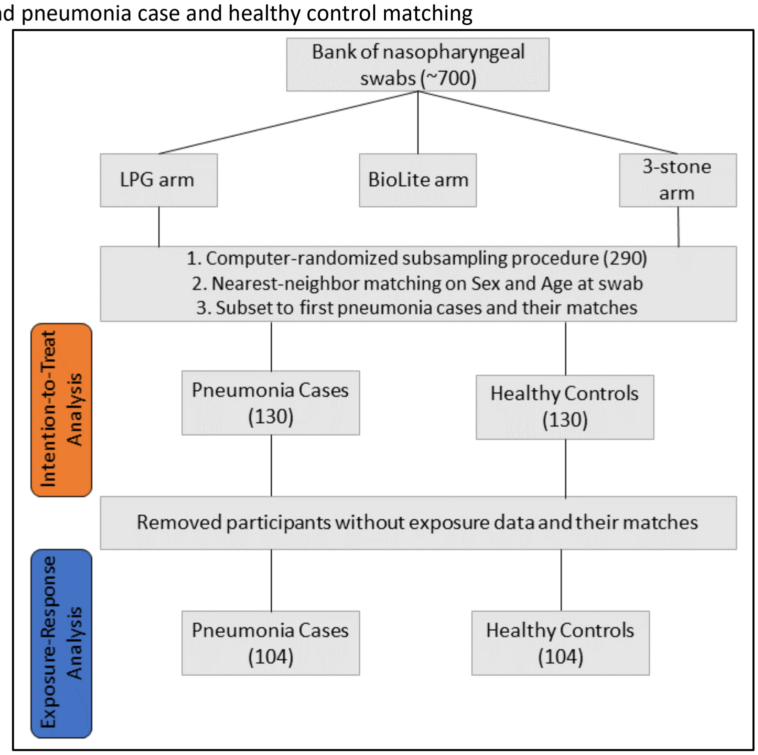
Study Participants

Participants were drawn from GRAPHS, a cluster-randomized cookstove intervention trial in the rural area of Kintampo, Ghana (Jack et al., 2015). Starting in August 2013, 1,414 non-smoking pregnant women were enrolled in GRAPHS. All women were enrolled by 24 weeks gestation, and were randomized to receive an improved biomass stove (Biolite), a liquefied petroleum gas (LPG) stove, or maintain use of the 3-stone fire, which is the traditional stove predominantly used in this part of Ghana. Mothers and infants were tracked until the infant's first birthday. LPG has been demonstrated to have the lowest air pollution emissions of the three types of stoves, whereas the 3-stone fire has the highest (Jetter et al., 2012).

Pneumonia Surveillance, Specimen Collection and Selection

Trained fieldworkers conducted weekly pneumonia surveillance according to the World Health Organization's Integrated Management of Childhood Illness (IMCI) guidelines. Fieldworkers referred suspected cases to a study clinic for clinician diagnosis and treatment. Nasopharyngeal swabs were taken for all clinician-diagnosed cases. Fieldworkers then identified healthy infant controls, who were also sent for nasopharyngeal swabs. A total of 669 unique samples were catalogued and stored for future analysis. Samples were stored in a -80°C freezer until microbial profiling, except for transport to the Unites States when on dry ice. With resources to analyze 290 samples, a computer-generated random selection of swabs were selected for PCR analysis (**Figure 1**). Swabs were only selected from the

Figure 1: Sample selection and pneumonia case and healthy control matching



LPG and 3-stone arms of the study to maximize the exposure contrast among samples. A nearest neighbor algorithm was used to match pneumonia cases with its nearest control. We then removed all repeat pneumonia cases, with their associated healthy controls, to preserve independence and given prior literature on altered microbiomal development with prior infection (Bosch et al., 2017). Our final sample consisted of 130 pneumonia cases and 130 healthy controls for our intention-to-treat analysis.

Carbon Monoxide Exposure

Personal exposure monitoring was conducted for carbon monoxide (CO) using the Lascar EL-CO-USB Data Logger (Erie, PA). Mother-child pairs had a total of ten 72-hour sessions throughout the study period, seven for the mother in the pre and postnatal period, and three for the child in the postnatal period. The monitor measured CO every ten seconds in parts per million. It was attached to the participants' clothing, close to the breathing zone, except during sleep or bathing, when participants were asked to keep the monitor off the ground and nearby. Fieldworkers visited daily to ensure wearing compliance and proper device functioning. Devices were checked against certified span gas every six weeks, and a data validation system addressed low-quality deployments. Final session values were based on the first 48 hours of deployment to maintain comparability of measurements between participants, i.e. premature battery failure yielding different device runtimes. See Quinn et al. for additional information (2016). Two separate exposure variables were used to assess effects based on timing of exposure. First, a prenatal maternal exposure average was calculated using the data from the four prenatal sessions, herein referred to as the *Mean Prenatal CO*. Second, for the postnatal session, children's exposures were linearly interpolated between time points to provide regular estimates over time. The interpolation estimates the most recent CO value at the time of the nasopharyngeal swab, herein referred to as *Recent CO*.

Ethical approvals

Ethical approvals for GRAPHS were obtained from the Ghana Health Service Ethical Review Committee, the Kintampo Health Research Centre Institutional Ethics Committee, and the Institutional

Review Board of Columbia University Medical Center.

Microbial Identification

MassTag polymerase chain reaction (PCR) was used to determine binary presence or absence of 22 common causes of childhood respiratory illness in 260 randomly selected banked samples, see **Table 1**. Total nucleic acid (TNA) from each sample was extracted with the EasyMag Extraction Platform (Biomerieux, Marcy l'Etoile, France). TNA (or cDNA, as appropriate) was used as template for MassTag PCR using two separate PCR multiplex assays. One assay targeted common respiratory RNA viruses, and the other targeted bacterial agents and adenovirus. Following the PCR, the products were purified and analyzed with a mass spectrometer for the presence of pathogen-specific tags (Briese et al., 2005; Lamson et al., 2006).

Table 1: Microbes Selected for MassTag PCR Analysis

DNA Agents	RNA Agents
Adenonvirus	Influenza A
Chlamydia pneumoniae	Influenza B
Legionella pneumophilia	Respiratory Syncytial Virus A (RSVA)
Mycoplasma pneumoniae	Respiratory Syncytial Virus B (RSVB)
Neisseria meningitidis	Human Parainfluenza Virus 1 (HPIV1)
Haemophilus influenzae	Human Parainfluenza Virus 2 (HPIV2)
Streptococcus pneumoniae	Human Parainfluenza Virus 3 (HPIV3)
Mycobacteria tuberculosis	Human Parainfluenza Virus 4 (HPIV4)
Moraxella catarrahalis	Human metapneumovirus (MPV)
Bortadella pertussis	Coronavirus OC43
	Coronavirus 229E
	Enterovirus

Viral and Bacterial Carriage by Study Arm

We first analyzed results via pairwise comparisons of summed microbial species identifications by study arm, comparing the 3-stone fire arm to the intervention arm (LPG cookstove). Summed species totals could vary from zero to 22: 0 to 9 for bacteria, and 0 to 13 for viruses. Comparisons were then conducted specific to bacteria and viruses. Count data of microbes were not normally distributed; therefore, we used Wilcox rank sum tests to compare differences. Because the GRAPHS study was designed with pneumonia as a principal outcome, we present results for all participants, and then stratify by pneumonia disease status. Cases are expected to have higher microbial species abundance than controls given that upper respiratory colonization or infection is part of the etiology of pneumonia (CITE). However, we hypothesized that increased HAP exposure or being in the 3-stone fire study arm would be associated with higher numbers of bacterial species presence both in pneumonia cases and healthy controls, but that the differences would be exacerbated among pneumonia cases.

Bacterial species presence by study arm was analyzed using contingency tables and Fisher's exact tests. Contingency tables were then used to calculate odds ratios, and confidence intervals were calculated with Bonferroni correction for multiple comparisons.

Exposure-Response Relationships Stratified by Disease Status

Analyses using the study arm as a proxy for exposure have the potential for exposure misclassification, as within-arm exposures exhibit considerable heterogeneity. We conducted exposure-response analyses, leveraging the individual-level personal exposure data for mothers and infants in the GRAPHS study.

Microbial Carriage. The outcome measures of interest were binary: testing positive or negative for each specific bacterium or virus. Bonferroni correction was used for multiple comparisons – therefore a p-value of 0.017 is considered statistically significant.

Covariates and confounding. Several variables were assessed as potential confounders due to theorized separate relationships with household air pollution and bacterial nasal carriage. They included an Asset Index (a measure of socioeconomic status), population density, total household size, and the season an infant was swabbed. The Asset Index was constructed using a principal components analysis of variables including: type of housing materials, type of toilet facility, primary water source, type of home ownership, household ownership of livestock animals, and household ownership of consumer durables (Gunnsteinsson et al., 2010). The population density measure was constructed using mapped census information from the Kintampo Health and Demographic Surveillance System. A 100-meter buffer was created around each home to aggregate the number of individuals per 100 meters using a spatial join. The season of swab was based on the date of an infant's swab, comparing the Harmattan/dry season to the non-Harmattan/wet season. Ultimately, we found that the season of swab was the only potential confounder variable correlated with the exposure and the outcome, and thus included in the final regression analyses. Age at swab and sex were also included in the analysis given a priori knowledge of relationships with the exposure and outcome.

Regressions and data analyses. Two generalized linear models were used in these analyses. First, logistic regression was used to model the odds of species-specific microbial presence given exposure. Then we used multinomial logistic regression to model the number of bacterial positives, comparing to zero, represented as follows:

$$\ln \frac{\Pr(Y_i = KBS)}{\Pr(Y_i = 0BS)} = \beta_{KBS} + \beta_1 \ln(CO) + \beta_2 ChildAge + \beta_3 ChildSex + \beta_4 SeasonSwabbed + \varepsilon,$$

where *KBS* = the number of bacterial species (1, 2, or 3), *0BS* = zero bacterial positives as the referent group, *CO* = measured carbon monoxide in parts per million, *ChildAge* = child's age in weeks, *ChildSex* = the child's biological sex at birth, *SeasonSwabbed* = whether the swab was during the wet or dry season. All exposure data had a substantial right skew and were transformed to the natural log scale for analysis. The regression models the likelihood of testing positive for one, two, or three bacterial species as a function of exposure. Therefore, the model is, in effect, blind to the particular species.

Missing Data and Sensitivity Analyses

While all mother-child pairs received personal exposure monitoring, not all participants had valid CO exposure assessments. This is because the study employed a strict quality control process that removed suspect values and identified device failures. Encouragingly, the baseline characteristics between those included in the intention-to-treat analyses and the exposure-response are not notably different (**Table 2**). However, we wanted to explore the degree to which this data loss could have influenced our results. Because mothers and their children were monitored concurrently, we were able to create a predictive model using a generalized additive model framework. We used the mother's exposure to predict the child's, also including relevant spatial and time-variant covariates such as: season, village coordinates, study treatment arm, and population density within 100 meters of the home. The model was cross-validated to limit the likelihood of overfitting. Predicted values were then included in the logistic and multinomial models and compared to the initial exposure-response results.

Buffers and spatial joins were conducted in QGIS 2.1. All other quantitative analyses were conducted in R version 3.3.3 (Vienna, Austria). The nearest-neighbor matching was performed with the *MatchIt* package. Multinomial models were estimated with the *nnet* package, and generalized additive models were estimated with the *mgcv* package. All three packages are available on CRAN.

Results:

Baseline demographics

Table 2 outlines the baseline demographics of the study participants, stratified by cases and controls. Variables included are those that might contribute to differences in microbial carriage, including breastfeeding, the child's age at the time of swab, household density, and season of birth. The only variable that which shows a marginal difference is the child's age at swab. This points to the importance of including this variable in our adjusted exposure-response analyses. Cases and controls show balance on all relevant covariates for exposure-response analyses.

Microbial Identification

MassTag PCR analysis yielded positives for 13 of the 22 microbes listed in **Table 1**. Three of the microbes were bacteria: *M. catarrhalis*, *S. pneumoniae and H. influenzae*. The positively identified viruses were: Rhinovirus, Influenza A, HPIV1, HPIV2, HPIV3, Metapneumovirus, Corona NL63, Corona OC43, RSVA, and Adenovirus (**Supplementary Table 1**).

Table 2: Baseline demographics, comparing pneumonia cases and healthy controls. P values derived from t-test if continuous or chi squared test if categorical.

	Intention-to-treat Analyses			**Exposure-Response Analyses**		
	Cases	***Controls***	***p***	***Cases***	***Controls***	***p***
n	130	130		104	104	
LPG/3-stone fire participants (n)	63/67	75/55		41/63	60/44	
Postnatal CO Exposure in ppm (Median (IQR))	-*	-*		0.64 (0.29-1.23)	0.78 (0.28-1.42)	
Mother's ethnicity (n (%))			0.73			0.56
Akan	16 (12.3)	24 (18.5)		12 (11.5)	21 (20.2)	
Dagarti	30 (23.1)	26 (20.0)		25 (24.0)	22 (21.2)	
Gonja	15 (11.5)	17 (13.1)		12 (11.5)	11 (10.6)	
Konkonba	18 (13.8)	13 (10.0)		15 (14.4)	10 (9.6)	
Mo	17 (13.1)	17 (13.1)		16 (15.4)	14 (13.5)	
Other	34 (26.2)	33 (25.4)		24 (23.1)	26 (25.0)	
Asset Index (mean (sd))	0.18 (2.14)	0.43 (2.24)	0.36	0.23 (2.14)	0.59 (2.33)	0.26
Caesarean birth (n (%))	5 (3.9)	10 (7.7)	0.29	3 (2.9)	7 (6.7)	0.33
Birth season = Wet (n (%))	70 (53.8)	69 (53.1)	1.00	60 (57.7)	56 (53.8)	0.68
Child's Sex = Female (n (%))	62 (47.7)	58 (44.6)	0.71	46 (44.2)	46 (44.2)	1.00
Breastfed within 4 days (n (%))	124 (96.1)	123 (94.6)	0.78	99 (95.2)	99 (95.2)	1.00
Season swabbed = Wet (n (%))	100 (76.9)	105 (80.8)	0.54	76 (73.1)	86 (82.7)	0.13
Age at Swab, in weeks (mean (sd))	21.16 (13.56)	24.45 (12.72)	0.06	22.66 (13.71)	24.56 (13.02)	0.31
Children <5 in household (mean (sd))**	1.12 (0.94)	1.16 (0.97)	0.74	1.09 (0.95)	1.13 (0.86)	0.75
Persons in household (mean (sd))	6.82 (3.86)	6.81 (3.20)	0.98	6.53 (3.41)	6.83 (3.22)	0.51
Population within 100 meters (mean (sd))	180.33 (95.40)	177.69 (96.25)	0.83	182.03 (98.71)	184.01 (101.22)	0.89

** Values were not calculated due to missing exposure data in some participants. **Not including participant child*

Viral and Bacterial Carriage by Study Arm

Results from the Wilcox rank sum analyses show that infants in the 3-stone fire arm had a higher abundance of all microbe species compared to infants in the LPG arm ($p<0.0001$) (**Table3**). This relationship appears to be driven by more numerous bacterial species ($p<0.0001$) rather than viral species, which showed no significant differences between arms. Stratifying the analysis by pneumonia status shows that clinician-diagnosed cases maintain the same relationship, with higher overall microbial ($p<0.001$) and higher bacterial ($p<0.0001$) species abundance. Again, there were no differences in viral presence. Healthy controls show a similar pattern, with marginally significant differences for all microbes ($p=0.058$), differences in bacterial species abundance ($p=0.011$), and no differences in viral species abundance. These results warranted particular emphasis on bacterial species, rather than viruses, because there were no observed differences in viral abundance. There is also a temporal pattern of bacterial carriage in the whole cohort, whereby overall carriage increases with a child's age (**Supplemental Figure 1**).

Table 3: Mean (median) identified microbial species presence for participants in the treatment Arm (LPG) to the Control Arm (3 stone), stratified by disease status. P values calculated from Wilcox rank sum test.

	All Participants (n = 260)			**Cases** (n = 130)			**Controls** (n = 130)		
	LPG (n=138)	3 Stone (n=122)	p value	LPG (n=63)	3 Stone (n=67)	p value	LPG (n=75)	3 Stone (n=55)	p value
All Microbes	2.71 (3)	3.34 (4)	<0.0001	2.95 (3)	3.70 (4)	<0.001	2.51 (2)	2.91 (3)	0.058
Viruses	0.97 (1)	0.98 (1)	0.964	1.22 (1)	1.15 (1)	0.457	0.76 (1)	0.76 (1)	0.83
Bacteria	1.74 (1)	2.37 (1)	<0.0001	1.73 (2)	2.55 (3)	<0.0001	1.75 (2)	2.15 (2)	0.011

These analyses show that infants in the 3-stone arm are more likely to test positive for all of the bacterial species compared to those in the LPG arm of the study (**Table 4**). This relationship is consistent for cases as well. Among healthy controls there is no difference in bacterial presence by study arm. Given our a priori hypothesis of higher bacterial species presence, we limited species-specific pairwise statistical analysis to *H.influenzae*, *S.pneumoniae*, *and M.catarrhalis*, with Bonnferoni correction.

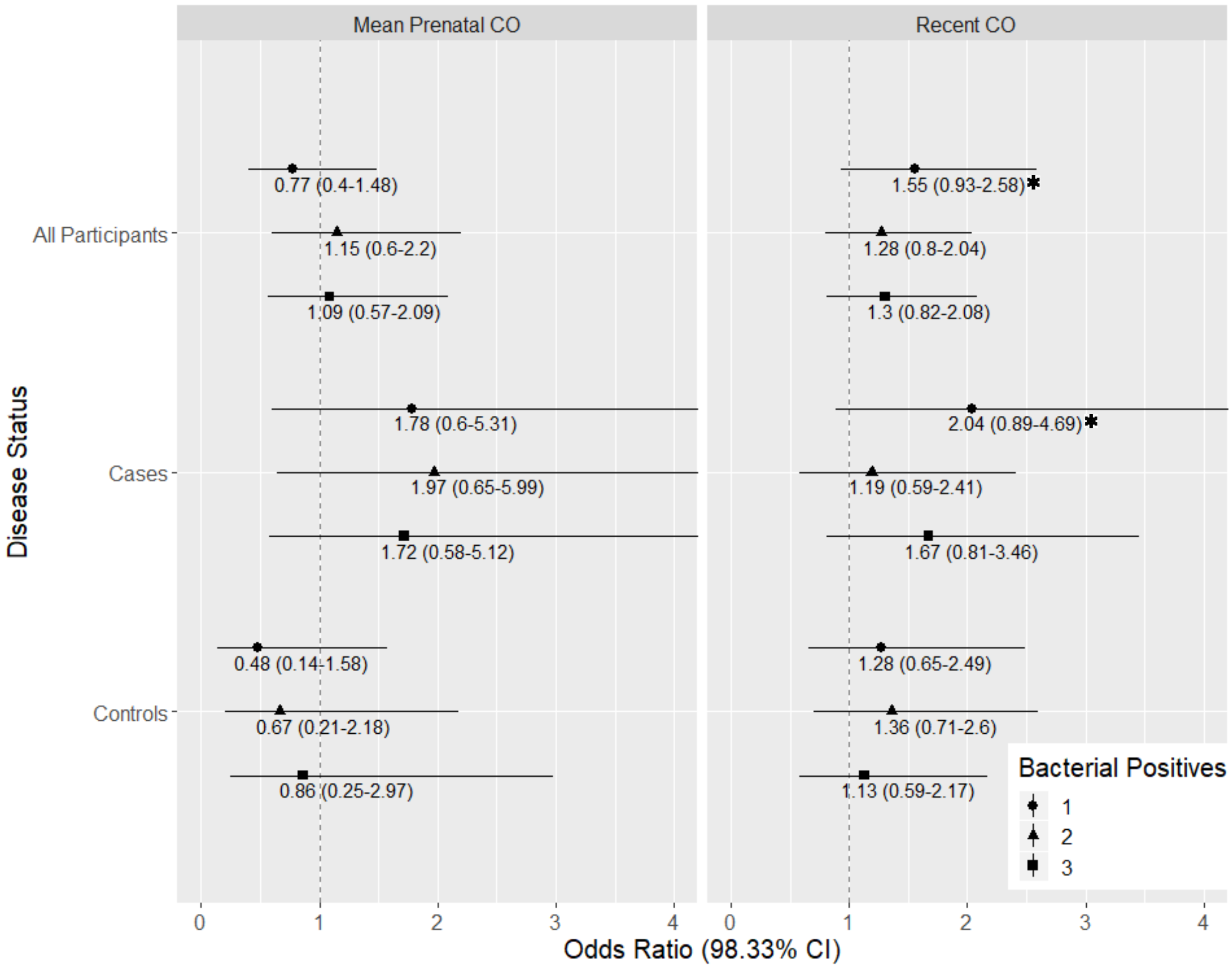
Table 4: Odds ratios (98.34% confidence intervals) comparing the number of species positives for infants in the 3-stone arm compared to those in the LPG/intervention arm. Statistically significant values, calculated from Fischer's exact test, in bold.

	All Infants (n =260)	Cases (n = 130)	Controls (n = 130)
S.pneumoniae	**2.42** (1.07-5.81)	**3.4** (1.01-13.46)	1.73 (0.55-5.95)
M.catarrhalis	**3.06** (1.55-6.22)	**3.71** (1.27-11.96)	2.46 (0.97-6.48)
H.influenzae	**3.1** (1.59-6.18)	**5.82** (2.15-17.09)	1.69 (0.66-4.45)

Exposure-response relationships stratified by disease status

Species-specific logistic regression models produced null results for both exposure variables (Recent CO and Mean Prenatal CO) of interest (**Supplementary Table 2**). Multinomial logistic regressions were employed to model potential exposure-response relationships of increasing levels of bacterial carriage (**Figure 2**). None of these models was statistically significant at the Bonferroni-adjusted confidence levels. However, the Recent postnatal CO regression has a suggestive finding whereby testing positive for one bacterial species increases with the child's most recent exposure (OR: 1.55, 98.33% CI: 0.93-2.58, p = 0.036). This trend appears to hold for cases (OR: 2.04, CI: 0.89-4.69, p = 0.038), but not controls.

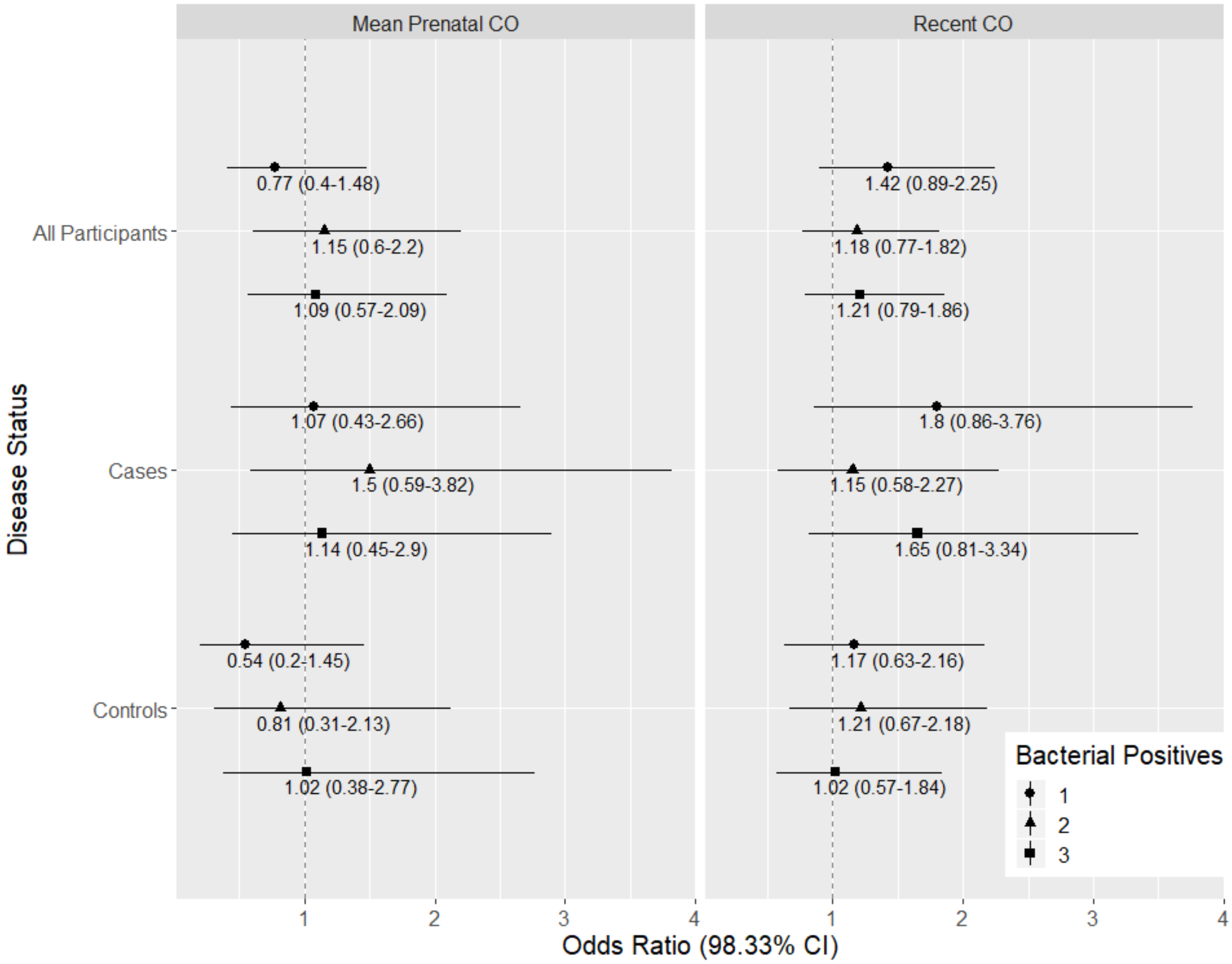
Figure 2: Results from multinomial logistic regression examining the effect of a log-unit increase of CO on number of bacterial positives (referent = 0, max = 3). Point estimate odds ratios are indicated by periods, and 98.34% confidence intervals by horizontal lines. All models adjusted for age at swab, sex, and season swabbed. P values < 0.05 are starred, but the Bonferroni-adjusted p value is 0.017. N = 208.



Sensitivity analysis

Mother-child pairings were leveraged to predict children's CO when missing, and used in our regression modeling. Analyses show similar patterns to the initial regression results, except virtually all effect estimates move towards the null (**Figure 3**). The suggestive finding of increased presence of one bacterium with most recent postnatal exposure also diminishes (OR: 1.42, CI: 0.89-2.25, p = 0.069).

Figure 3: Results from the sensitivity analysis, predicting CO levels for missing observations. A multinomial logistic regression examining the effect of a log-unit increase of CO on number of bacterial positives (referent = 0, max = 3). Point estimate odds ratios are indicated by dots, and 98.34% confidence intervals by horizontal lines. All models adjusted for age at swab, sex, and season swabbed. P values < 0.05 are starred, but the Bonferroni-adjusted p value is 0.017. N = 260.



Discussion

We conducted a study in a rural region of Ghana analyzing infant microbial carriage in relation to household air pollution exposures and cookstove interventions. Using MassTag PCR of nasopharyngeal swabs, we identified ten viruses and three bacteria present among our study participants. In an intention-to-treat analysis, we observed decreased bacterial species presence among participants in the LPG study arm, but not in the 3-stone fire study arm. This observation persisted among all three of the bacterial species analyzed. The trend was pronounced for pneumonia cases, and attenuated for healthy controls. We did not observe a difference in viral species presence between the

LPG and 3-stone study arms. This finding is consistent with other studies in Guatemala and Malawi (Rylance et al., 2015; Smith et al., 2011; Zhou & Kobzik, 2007) that suggest that pneumonias identified in settings with high HAP exposure may be of bacterial rather than viral origin.

Our models did not yield statistically significant findings in our exposure-response analyses of bacterial carriage for pre or postnatal exposure to CO after adjusting for multiple comparisons. A suggestive observation in our multinomial model indicates that postnatal HAP-exposure may increase the likelihood of testing positive for one bacterial species compared to none – either *H. influenzae*, *S. pneumoniae*, or *M. catarrhalis*. This is consistent with research indicating that exposure to air pollution may damage the nasal epithelium and cilia of children (Calderón-Garcidueñas et al., 2001; Glück & Gebbers, 2000). The damaged nasal tissue, therefore, may be more hospitable to bacterial inhabitance. Relationships between bacteria may then facilitate acquisition of additional bacteria (Abdullahi, Nyiro, Lewa, Slack, & Scott, 2008; Dunne et al., 2018; Shiri et al., 2013; Tikhomirova & Kidd, 2013). However, subsequent sensitivity analysis showed an increased p value, likely due to a noisier exposure metric for predicted values. More research is needed to understand this potential dynamic.

The age at which exposure occurs is also emerging as an important variable in these investigations, as many air pollution studies indicate that risk changes over the life course (Goldizen, Sly, & Knibbs, 2016; Lee et al., 2018). This can have important ramifications for policy. For example, if the antenatal period comprises a window of susceptibility, then policies that target exposure reductions to pregnant women may be particularly effective. We, however, find no evidence of an effect of prenatal air pollution exposure on nasal carriage.

This study has many strengths, including cookstove randomization, robust disease surveillance, and exposure monitoring. Past studies in this field either have lacked specificity in the microbes tested for or a prospective study design, thus limiting the ability to account for confounding factors (Smith et al., 2011; Rylance et al., 2016). Our analysis is nested in a well-characterized longitudinal cohort tracked in the prenatal and postnatal periods. Therefore, we are able to assess the potential roles of antenatal exposures on microbial carriage, which has not been previously examined to our knowledge. Although there was random missingness in the exposure-response analyses, available maternal exposure data, and relevant spatial and time-variant predictors allowed us to predict children's exposure.

There are limitations to our analysis. With regard to exposure, we are limited by the fact that CO was the only consistently monitored air pollutant. When designing the study, we intended to use CO as a proxy for fine particulate matter ($PM_{2.5}$). Since then, studies have demonstrated that CO may not be an appropriate proxy (Carter et al., 2017; Klasen et al., 2015). $PM_{2.5}$ was monitored in this trial, but due to the considerable cost of $PM_{2.5}$ exposure monitoring relative to CO, it was only monitored on a subset of participants in fewer monitoring sessions. We investigated using PM exposures in the current analysis, but there was not sufficient overlap between swabbed participants and those tracked for $PM_{2.5}$ in order to conduct exposure-response analyses. PM from biomass combustion has been shown to impair macrophage response, but no such evidence exists for CO (Rylance et al., 2015, 2016; Zhou & Kobzik, 2007).

Another potential limitation to this study is the high prevalence of bacterial nasal carriage in the overall population, thus limiting our power to detect differences. Although we were unable to find literature about Ghana specifically, there is evidence of high bacterial carriage of pneumococcal bacteria and *H.influenzae* in West Africa, specifically in the Gambia and Nigeria (Adetifa et al., 2012; Goetghebuer et al., 2000; Hill et al., 2008). These high background levels mean that our study may not have been appropriately powered to detect differences in bacterial abundance. Further, MassTag PCR, while a powerful tool, provides coarse measures of microbial diversity. Results from the MassTag PCR can only provide a binary outcome on a fixed library of microbes. More recent evidence suggests that the presence of a microbe does not provide adequate information to understand the inner workings of the respiratory microbiome. Finally, our analysis utilizes samples from the nasal epithelium whereas pneumonia occurs in the lower respiratory tract. However, growing evidence demonstrates the strong relationships between the composition of the upper respiratory tract and overall respiratory health (Biesbroek et al., 2014; Man, de Steenhuijsen Piters, & Bogaert, 2017; Teo et al., 2015).

Conclusion

To our knowledge, this is the first analysis assessing measured HAP-exposure and microbial carriage nested in a longitudinal cohort. Our findings support past literature that HAP-associated pneumonia may be bacterial rather than viral in origin. This is an important area of investigation given the vast burden of disease caused by HAP, specifically on young children. Identification of the underlying etiologic relationships can spur advancements in vaccination or infection control, but exposure reduction is the ultimate prevention tool.

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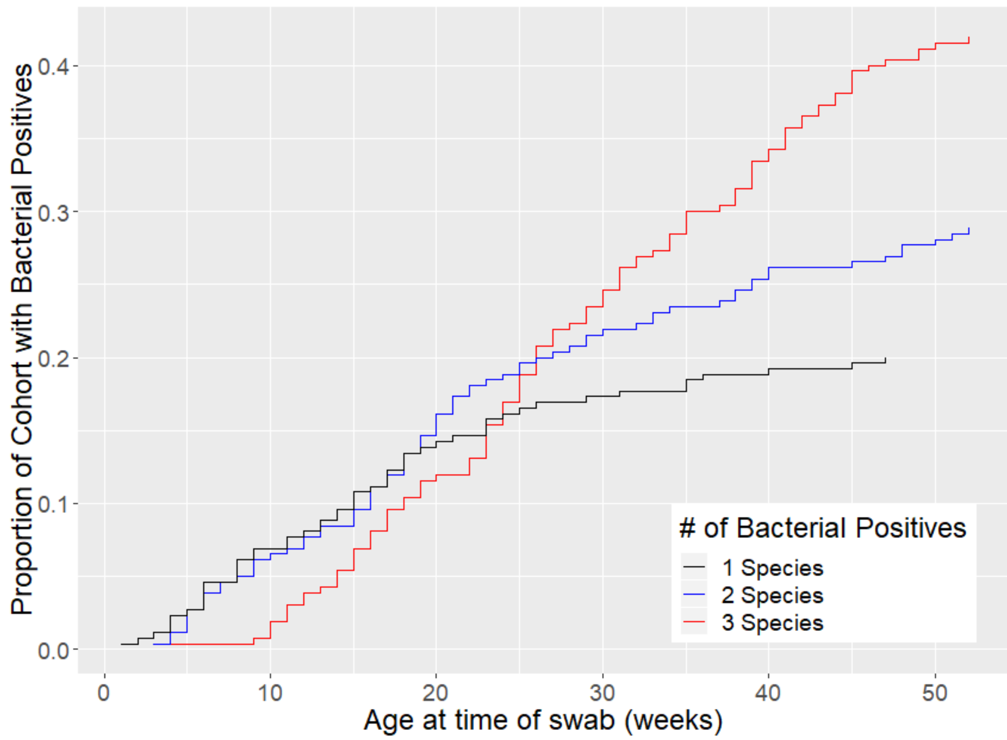
Supplemental Materials

Supplemental Table 1: MassTag PCR results, count of positives by arm of study and disease status (n = 260)

	All Samples		**Cases**		**Controls**	
Arm (n)	*3 Stone* (n = 122)	*LPG* (n = 138)	*3 Stone* (n = 67)	*LPG* (n = 63)	*3 Stone* (n = 55)	*LPG* (n = 75)
Rhinovirus	79	87	44	48	35	39
Influenza A	3	5	3	3	0	2
HPIV1	5	6	3	3	2	3
HPIV2	3	2	3	1	0	1
HPIV3	10	22	7	18	3	4
Metapneumovirus	4	1	4	0	0	1
Corona NL63	5	8	4	4	1	4
Corona OC43	5	0	4	0	1	0
RSVA	4	0	4	0	0	0
H.influenzae	89	67	54	26	35	41
S. pneumoniae	106	101	60	45	46	56
M.catarrhalis	94	72	57	38	37	34
Adenovirus	1	3	1	0	0	3

Supplemental Figure 1: Cumulative proportion of swabs (n = 260) that tested positive for bacterial species by child's age.



Supplemental Table 2: Odds ratios from logistic regressions with corresponding p values. All models adjusted for age at swab, sex, and season swabbed.

Species presence	Disease status	Recent CO	p value	Prenatal Mean CO	p value
H. influenzae	All Participants	1.14	0.22	1.20	0.29
	Cases	1.14	0.44	1.18	0.53
	Controls	1.15	0.33	1.26	0.36
M. catarrhalis	All Participants	0.85	0.15	1.26	0.20
	Cases	0.99	0.97	1.26	0.41
	Controls	0.83	0.22	1.23	0.41
S. pneumoniae	All Participants	1.12	0.39	0.99	0.96
	Cases	1.31	0.16	1.09	0.78
	Controls	1.03	0.86	0.86	0.62

Supplemental Table 3: Odds ratios from multinomial logistic regressions with corresponding p values. All models adjusted for age at swab, sex, and season swabbed.

Species	Disease status	Recent CO	p value	Mean Prenatal CO	p value
1	All Participants	1.55	**0.038**	0.92	0.789
	Cases	2.04	**0.039**	1.78	0.207
	Controls	1.28	0.383	0.48	0.139
2	All Participants	1.28	0.216	1.23	0.505
	Cases	1.19	0.556	1.97	0.144
	Controls	1.36	0.264	0.67	0.415
3	All Participants	1.30	0.177	1.24	0.484
	Cases	1.67	0.092	1.72	0.237
	Controls	1.13	0.661	0.86	0.773

References

Abdullahi, O., Nyiro, J., Lewa, P., Slack, M., & Scott, J. A. G. (2008). The descriptive epidemiology of Streptococcus pneumoniae and Haemophilus influenzae nasopharyngeal carriage in children and adults in Kilifi district, Kenya. *The Pediatric Infectious Disease Journal*, *27*(1), 59.

Adetifa, I. M. O., Antonio, M., Okoromah, C. A. N., Ebruke, C., Inem, V., Nsekpong, D., … Adegbola, R. A. (2012). Pre-Vaccination Nasopharyngeal Pneumococcal Carriage in a Nigerian Population: Epidemiology and Population Biology. *PLoS ONE*, *7*(1). https://doi.org/10.1371/journal.pone.0030548

Asuman, D., Ackah, C. G., & Enemark, U. (2018). Inequalities in child immunization coverage in Ghana: evidence from a decomposition analysis. *Health Economics Review*, *8*. https://doi.org/10.1186/s13561-018-0193-7

Biesbroek, G., Tsivtsivadze, E., Sanders, E. A. M., Montijn, R., Veenhoven, R. H., Keijser, B. J. F., & Bogaert, D. (2014). Early Respiratory Microbiota Composition Determines Bacterial Succession Patterns and Respiratory Health in Children. *American Journal of Respiratory and Critical Care Medicine*, *190*(11), 1283–1292. https://doi.org/10.1164/rccm.201407-1240OC

Bonjour, S., Adair-Rohani, H., Wolf, J., Bruce, N. G., Mehta, S., Prüss-Ustün, A., … Smith, K. R. (2013). Solid Fuel Use for Household Cooking: Country and Regional Estimates for 1980–2010. *Environmental Health Perspectives*, *121*(7), 784–790. https://doi.org/10.1289/ehp.1205987

Bosch, A. A. T. M., Piters, W. A. A. de S., van Houten, M. A., Chu, M. L. J. N., Biesbroek, G., Kool, J., … Bogaert, D. (2017). Maturation of the Infant Respiratory Microbiota, Environmental Drivers, and Health Consequences. A Prospective Cohort Study. *American Journal of Respiratory and Critical Care Medicine*, *196*(12), 1582–1590. https://doi.org/10.1164/rccm.201703-0554OC

Brauer, M., Hoek, G., Van Vliet, P., Meliefste, K., Fischer, P. H., Wijga, A., … Brunekreef, B. (2002). Air Pollution from Traffic and the Development of Respiratory Infections and Asthmatic and Allergic Symptoms in Children. *American Journal of Respiratory and Critical Care Medicine*, *166*(8), 1092–1098. https://doi.org/10.1164/rccm.200108-007OC

Briese, T., Palacios, G., Kokoris, M., Jabado, O., Liu, Z., Renwick, N., … Lipkin, W. I. (2005). Diagnostic System for Rapid and Sensitive Differential Detection of Pathogens. *Emerging Infectious Diseases*, *11*(2), 310–313. https://doi.org/10.3201/eid1102.040492

Calderón-Garcidueñas, L., Valencia-Salazar, G., Rodríguez-Alcaraz, A., Gambling, T. M., García, R., Osnaya, N., … Carson, J. L. (2001). Ultrastructural Nasal Pathology in Children Chronically and

Sequentially Exposed to Air Pollutants. *American Journal of Respiratory Cell and Molecular Biology*, *24*(2), 132–138. https://doi.org/10.1165/ajrcmb.24.2.4157

Carter, E., Norris, C., Dionisio, K. L., Balakrishnan, K., Checkley, W., Clark, M. L., … Baumgartner, J. (2017). Assessing Exposure to Household Air Pollution: A Systematic Review and Pooled Analysis of Carbon Monoxide as a Surrogate Measure of Particulate Matter. *Environmental Health Perspectives*, *125*(7), 076002. https://doi.org/10.1289/EHP767

Dherani, M., Pope, D., Mascarenhas, M., Smith, K. R., Weber, M., & Bruce, N. (2008). Indoor air pollution from unprocessed solid fuel use and pneumonia risk in children aged under five years: a systematic review and meta-analysis. *Bulletin of the World Health Organization*, *86*, 390-398C.

Dunne, E. M., Murad, C., Sudigdoadi, S., Fadlyana, E., Tarigan, R., Indriyani, S. A. K., … Hinds, J. (2018). Carriage of Streptococcus pneumoniae, Haemophilus influenzae, Moraxella catarrhalis, and Staphylococcus aureus in Indonesian children: A cross-sectional study. *PloS One*, *13*(4), e0195098.

Glück, U., & Gebbers, J.-O. (2000). The Comet Assay of Nasal Epithelia: Measurement of DNA Damage for the Assessment of Genotoxic Air Pollution: The Comet Assay of Nasal Epithelia: Measurement of DNA Damage for the Assessment of Genotoxic Air Pollution. *The Laryngoscope*, *110*(1), 123–125. https://doi.org/10.1097/00005537-200001000-00022

Goetghebuer, T., West, T. E., Wermenbol, V., Cadbury, A. L., Milligan, P., Lloyd-Evans, N., … Weber, M. W. (2000). Outcome of meningitis caused by Streptococcus pneumoniae and Haemophilus influenzae type b in children in The Gambia. *Tropical Medicine & International Health*, *5*(3), 207–213.

Goldizen, F. C., Sly, P. D., & Knibbs, L. D. (2016). Respiratory effects of air pollution on children: Respiratory Effects of Air Pollution on Children. *Pediatric Pulmonology*, *51*(1), 94–108. https://doi.org/10.1002/ppul.23262

Gordon, S. B., Bruce, N. G., Grigg, J., Hibberd, P. L., Kurmi, O. P., Lam, K. H., … Balmes, J. (2014). Respiratory risks from household air pollution in low and middle income countries. *The Lancet Respiratory Medicine*, *2*(10), 823–860.

Gunnsteinsson, S., Labrique, A. B., West, K. P., Christian, P., Mehra, S., Shamim, A. A., … Klemm, R. D. (2010). Constructing Indices of Rural Living Standards in Northwestern Bangladesh. *Journal of Health, Population and Nutrition*, *28*(5). https://doi.org/10.3329/jhpn.v28i5.6160

Hill, P. C., Cheung, Y. B., Akisanya, A., Sankareh, K., Lahai, G., Greenwood, B. M., & Adegbola, R. A. (2008). Nasopharyngeal Carriage of Streptococcus pneumoniae in Gambian Infants: A Longitudinal Study. *Clinical Infectious Diseases*, *46*(6), 807–814. https://doi.org/10.1086/528688

Institute for Health Metrics and Evaluation. (2017). Global Burden of Disease Study. Retrieved November 13, 2018, from http://ghdx.healthdata.org/gbd-2017

Jack, D. W., Asante, K. P., Wylie, B. J., Chillrud, S. N., Whyatt, R. M., Quinn, A. K., … Mujtaba, M. (2015). Ghana randomized air pollution and health study (GRAPHS): study protocol for a randomized controlled trial. *Trials*, *16*(1), 420.

Jetter, J., Zhao, Y., Smith, K. R., Khan, B., Yelverton, T., DeCarlo, P., & Hays, M. D. (2012). Pollutant Emissions and Energy Efficiency under Controlled Conditions for Household Biomass Cookstoves and Implications for Metrics Useful in Setting International Test Standards. *Environmental Science & Technology*, *46*(19), 10827–10834. https://doi.org/10.1021/es301693f

Klasen, E. M., Wills, B., Naithani, N., Gilman, R. H., Tielsch, J. M., Chiang, M., … Apaka, C. (2015). Low correlation between household carbon monoxide and particulate matter concentrations from biomass-related pollution in three resource-poor settings. *Environmental Research*, *142*, 424–431.

Lamson, D., Renwick, N., Kapoor, V., Liu, Z., Palacios, G., Ju, J., … Ian Lipkin, W. (2006). MassTag Polymerase-Chain-Reaction Detection of Respiratory Pathogens, Including a New Rhinovirus Genotype, That Caused Influenza-Like Illness in New York State during 2004–2005. *The Journal of Infectious Diseases*, *194*(10), 1398–1402. https://doi.org/10.1086/508551

Lee, A. G., Kaali, S., Quinn, A., Delimini, R., Burkart, K., Opoku-Mensah, J., … Asante, K. P. (2018). Prenatal Household Air Pollution is Associated with Impaired Infant Lung Function with Sex-Specific Effects: Evidence from GRAPHS, a Cluster Randomized Cookstove Intervention Trial. *American Journal of Respiratory and Critical Care Medicine*. https://doi.org/10.1164/rccm.201804-0694OC

MacIntyre, E. A., Gehring, U., Mölter, A., Fuertes, E., Klümper, C., Krämer, U., … Heinrich, J. (2014). Air Pollution and Respiratory Infections during Early Childhood: An Analysis of 10 European Birth Cohorts within the ESCAPE Project. *Environmental Health Perspectives*, *122*(1), 107–113. https://doi.org/10.1289/ehp.1306755

Man, W. H., de Steenhuijsen Piters, W. A. A., & Bogaert, D. (2017). The microbiota of the respiratory tract: gatekeeper to respiratory health. *Nature Reviews Microbiology*, *15*(5), 259–270. https://doi.org/10.1038/nrmicro.2017.14

Mortimer, K., Ndamala, C. B., Naunje, A. W., Malava, J., Katundu, C., Weston, W., … Nyirenda, M. (2017). A cleaner burning biomass-fuelled cookstove intervention to prevent pneumonia in children under 5 years old in rural Malawi (the Cooking and Pneumonia Study): a cluster randomised controlled trial. *The Lancet*, *389*(10065), 167–175.

Quinn, A. K., Ae-Ngibise, K. A., Jack, D. W., Boamah, E. A., Enuameh, Y., Mujtaba, M. N., … Asante, K. P. (2016). Association of Carbon Monoxide exposure with blood pressure among pregnant women in rural Ghana: Evidence from GRAPHS. *International Journal of Hygiene and Environmental Health*, *219*(2), 176–183. https://doi.org/10.1016/j.ijheh.2015.10.004

Romieu, I., Samet, J. M., Smith, K. R., & Bruce, N. (2002). Outdoor Air Pollution and Acute Respiratory Infections Among Children in Developing Countries. *Journal of Occupational and Environmental Medicine*, *44*(7). Retrieved from https://journals.lww.com/joem/Fulltext/2002/07000/Outdoor_Air_Pollution_and_Acute_Respiratory.10.aspx

Rudan, I. (2008). Epidemiology and etiology of childhood pneumonia. *Bulletin of the World Health Organization*, *86*(5), 408–416. https://doi.org/10.2471/BLT.07.048769

Rylance, J., Chimpini, C., Semple, S., Russell, D. G., Jackson, M. J., Heyderman, R. S., & Gordon, S. B. (2015). Chronic Household Air Pollution Exposure Is Associated with Impaired Alveolar Macrophage Function in Malawian Non-Smokers. *PLOS ONE*, *10*(9), e0138762. https://doi.org/10.1371/journal.pone.0138762

Rylance, J., Kankwatira, A., Nelson, D. E., Toh, E., Day, R. B., Lin, H., … Gordon, S. B. (2016). Household air pollution and the lung microbiome of healthy adults in Malawi: a cross-sectional study. *BMC Microbiology*, *16*(1). https://doi.org/10.1186/s12866-016-0803-7

Shiri, T., Nunes, M. C., Adrian, P. V., Van Niekerk, N., Klugman, K. P., & Madhi, S. A. (2013). Interrelationship of Streptococcus pneumoniae, Haemophilus influenzae and Staphylococcus aureus colonization within and between pneumococcal-vaccine naïve mother-child dyads. *BMC Infectious Diseases*, *13*, 483. https://doi.org/10.1186/1471-2334-13-483

Smith, K. R. (2000). Indoor air pollution in developing countries and acute lower respiratory infections in children. *Thorax*, *55*(6), 518–532. https://doi.org/10.1136/thorax.55.6.518

Smith, Kirk R., Bruce, N., Balakrishnan, K., Adair-Rohani, H., Balmes, J., Chafe, Z., … Rehfuess, E. (2014). Millions Dead: How Do We Know and What Does It Mean? Methods Used in the Comparative Risk Assessment of Household Air Pollution. *Annual Review of Public Health*, *35*(1), 185–206. https://doi.org/10.1146/annurev-publhealth-032013-182356

Smith, Kirk R, McCracken, J. P., Weber, M. W., Hubbard, A., Jenny, A., Thompson, L. M., … Bruce, N. (2011). Effect of reduction in household air pollution on childhood pneumonia in Guatemala (RESPIRE): a randomised controlled trial. *The Lancet*, *378*(9804), 1717–1726. https://doi.org/10.1016/S0140-6736(11)60921-5

Teo, S. M., Mok, D., Pham, K., Kusel, M., Serralha, M., Troy, N., … Inouye, M. (2015). The Infant Nasopharyngeal Microbiome Impacts Severity of Lower Respiratory Infection and Risk of Asthma Development. *Cell Host & Microbe*, *17*(5), 704–715. https://doi.org/10.1016/j.chom.2015.03.008

Tikhomirova, A., & Kidd, S. P. (2013). Haemophilus influenzae and Streptococcus pneumoniae: living together in a biofilm. *Pathogens and Disease*, *69*(2), 114–126. https://doi.org/10.1111/2049-632X.12073

Troeger, C., Forouzanfar, M., Rao, P. C., Khalil, I., Brown, A., Swartz, S., … Mokdad, A. H. (2017). Estimates of the global, regional, and national morbidity, mortality, and aetiologies of lower respiratory tract infections in 195 countries: a systematic analysis for the Global Burden of Disease Study 2015. *The Lancet Infectious Diseases*, *17*(11), 1133–1161. https://doi.org/10.1016/S1473-3099(17)30396-1

UNICEF. (2018, February). *Estimates of child cause of death, Acute Respiratory Infection 2018*. Retrieved from https://data.unicef.org/topic/child-health/pneumonia/

Walker, C. L. F., Rudan, I., Liu, L., Nair, H., Theodoratou, E., Bhutta, Z. A., … Black, R. E. (2013). Global burden of childhood pneumonia and diarrhoea. *The Lancet*, *381*(9875), 1405–1416.

Weber, M. W., Milligan, P., Hilton, S., Lahai, G., Whittle, H., Mulholland, E. K., & Greenwood, B. M. (1999). Risk factors for severe respiratory syncytial virus infection leading to hospital admission in children in the Western Region of The Gambia. *International Journal of Epidemiology*, *28*(1), 157–162.

World Health Organization. (2016). Pneumonia. Retrieved November 13, 2018, from World Health Organization website: http://www.who.int/news-room/fact-sheets/detail/pneumonia

Zhou, H., & Kobzik, L. (2007). Effect of Concentrated Ambient Particles on Macrophage Phagocytosis and Killing of Streptococcus pneumoniae. *American Journal of Respiratory Cell and Molecular Biology*, *36*(4), 460–465. https://doi.org/10.1165/rcmb.2006-0293OC

CHAPTER 2

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Title: Using longitudinal survey and sensor data to understand the social and ecological determinants of suspended clean cookstove use in rural Ghana

Abstract

Background: Three billion people use biomass for cooking and/or heating. Efforts to reduce the health and ecological burdens of biomass use are underway, principally encouraging clean or improved cookstoves. Studies often examine factors associated with sustained use of clean cookstoves, but cookstove suspension is a novel framework to understand the impediments of clean cookstove use, and reasons for disuse. Ghana, the research location, has a national energy plan to scale up clean cooking and represents a policy-relevant setting for the suspended use paradigm.

Methods: We leverage data from the Ghana Randomized Air Pollution and Health Study (GRAPHS) (n=1412). Households received one of two intervention stoves: an improved biomass stove (BioLite) or an LPG stove. LPG users were given free LPG refills during GRAPHS. Weekly stove use questionnaires were administered. A sub cohort (n = 220) was tracked via stove use monitors, 6 months before and after the fuel subsidy. Here we study the social and ecological determinants of stove disuse and suspension.

Results: 60% of BioLite participants and 80% of LPG participants report intervention stove use by GRAPHS' end date. Participants reported using intervention stoves less for large meals or those requiring vigorous stirring. Experiencing burns from intervention stoves yields a 4.4 percentage point stove use reduction among LPG users ($p<0.001$) and 2.5 reduction among BioLite ($p<0.001$). Survival analysis demonstrates increased proportions of tree canopy within a 3-kilometer buffer is the only variable explaining LPG suspended stove use (HR = -0.56, $p<0.0001$).

Conclusions: Future studies should consider the stove use suspension framework. Additionally, we recommend the Ghanaian government consider incorporating health promotion methods in LPG outreach efforts.

Introduction

Increasing the availability and uptake of clean cooking fuels has become an international goal, evidenced by the Sustainable Development Goals and Sustainable Energy for All initiative ("Sustainable Energy for All," 2019). Ghana is one of many countries in Sub-Saharan Africa attempting to decrease biomass use, while increasing the use of improved and clean cooking technologies (ENERGIA, 2015; World Bank, 2014). The Government of Ghana established a Sustainable Energy for All policy in 2008, with a target of 50% of the population using LPG by 2020 (Energy-Commission, 2012). Unfortunately it is unlikely that Ghana will reach those targets (Asante et al., 2018). We believe that research is warranted to understand why Ghana will not reach these targets. These efforts may inspire the design of new, evidence-based, policies that effectively increase clean cooking.

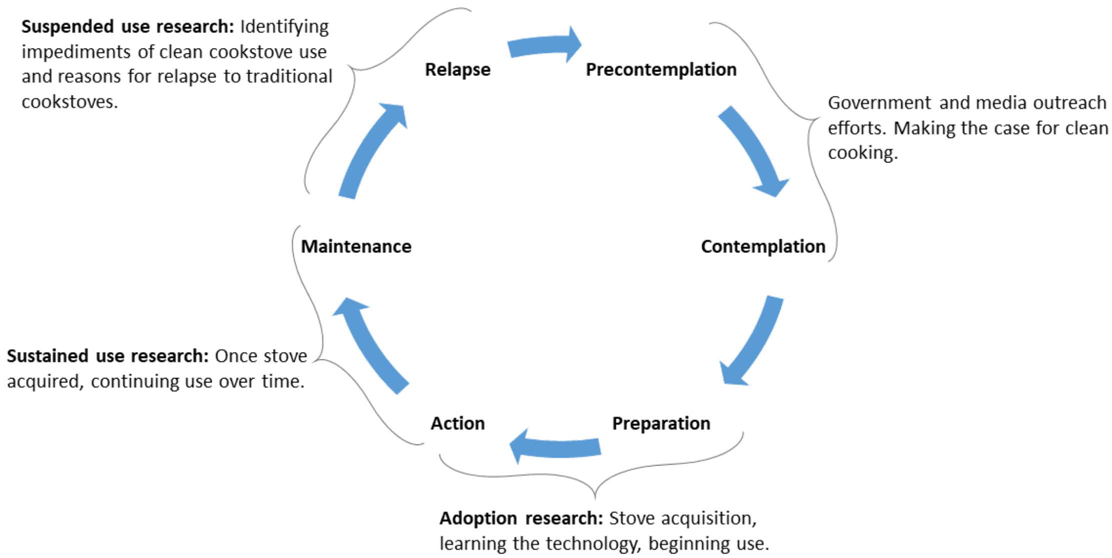
Initiated in 2013 in response to observed low LPG uptake in rural areas and concerns of deforestation, the Ghana Rural LPG Progamme offers free LPG stoves and cylinders in poor rural villages (Asante et al., 2018; Modern Ghana, 2011). An evaluation of the Rural LPG Programme found extremely low levels of stove use among recipients, with less than 5% of beneficiaries demonstrating any use nine months after stove delivery (Abdulai et al., 2018). Reducing biomass use in rural areas is a worthwhile goal for health and ecological concerns, but those benefits can only be realized if stoves are used consistently over time. Studies demonstrate that near complete displacement of traditional fuels is required to reach the World Health Organization guidelines for exposure to particulate matter (Johnson & Chiang, 2015). Therefore, a long-standing and growing body of literature has focused on understanding the determinants of clean and improved cookstove adoption and sustained use in order to inform behavioral, programmatic, and policy interventions that would increase clean cookstove use (Muller & Yan, 2018; Puzzolo, Pope, Stanistreet, Rehfuess, & Bruce, 2016; Rehfuess, Puzzolo, Stanistreet, Pope, & Bruce, 2014). Few studies, however, have considered the opposite perspective: which factors cause people to decrease or stop using their clean cookstoves? Several studies report that participants stop using clean cookstoves during or soon after a study period (Hanna, Duflo, & Greenstone, 2016; Mudombi et al., 2018; Tigabu, 2017), but formally assessing the determinants of this cookstove abandonment has been minimal (Chalise, Kumar, Priyadarshini, & Yadama, 2018; Wang & Corson, 2015). In a novel effort, we present an empirical assessment of the factors that lead people to decrease and ultimately stop using their clean cookstoves – a phenomenon we term "suspension of clean cookstove use". By explicitly studying this phenomenon, we ultimately aim to prevent, or reduce the duration of stove use suspension, thus maximizing the health gains from clean cookstoves.

We leverage data from the Ghana Randomized Air Pollution & Health Study (GRAPHS), a cookstove intervention trial in rural Ghana (Jack et al., 2015), to explore impediments to intervention stove use and the social and ecological drivers of improved and clean cookstove suspension. We use survey and geospatial data to understand: 1) self-reported stove use, 2) self-reported reasons for not using an intervention stove, and 3) fuelwood collection time as a potential incentive for clean cookstove use. In addition, we make use of data collected with stove use monitors installed in a subset of households six months prior to the end of GRAPHS to objectively assess intervention stove use and estimate the impact of social and ecological factors on the suspension of clean cookstove use in a survival analysis.

Background

The notion of stove use suspension has its foundation in health behavior theory. According to the Transtheoretical (Stages of Change) Model, the adoption of healthy behaviors is not a linear endeavor (Prochaska & Velicer, 1997) (**Figure 1**). Adoption and sustained behavior change typically entails relapse to the old behavior. After relapse, some individuals restart efforts towards behavior change while others stop altogether. Many studies have investigated the determinants of relapse for physical activity, changes in diet, and smoking cessation, but none for clean cookstove use (Di Noia & Prochaska, 2010; Marshall & Biddle, 2001; Spencer, Pagell, Hallion, & Adams, 2002). Understanding the factors that contribute to stove use suspension can inform individual, community, and/or policy interventions to prevent suspension or shorten its duration. This would decrease personal air pollution exposures and the ecological impacts of biomass collection (Bailis, Drigo, Ghilardi, & Masera, 2015; Lacey, Henze, Lee, van Donkelaar, & Martin, 2017; Smith et al., 2014).

Figure 1: Adapted transtheoretical (Stages of Change) Model for clean cooking.

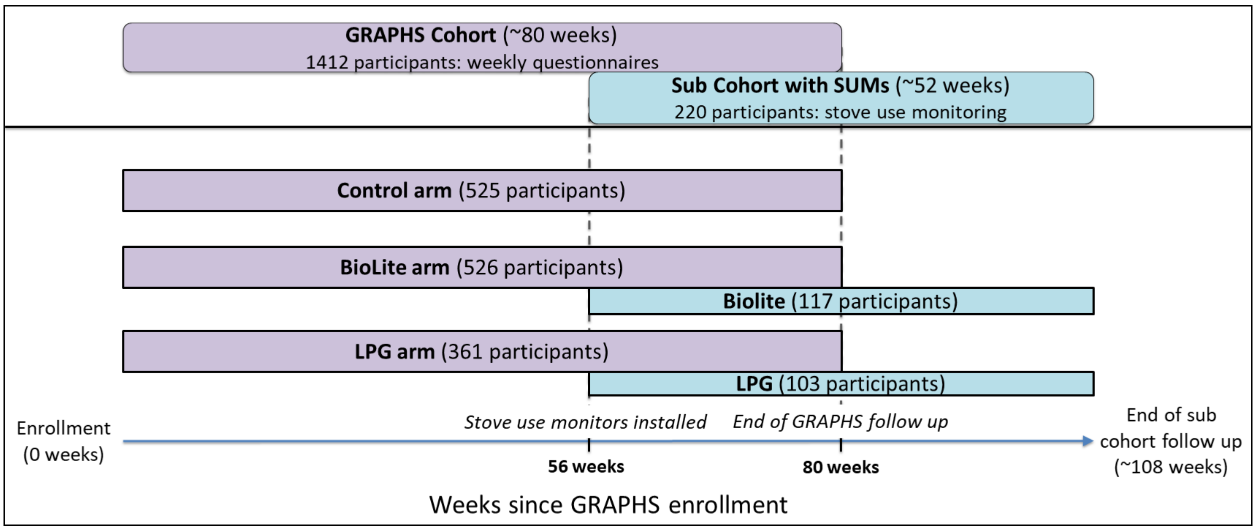


Methods

Study Participants & Context

The participants of this study are a sub-cohort of the Ghana Randomized Air Pollution and Health Study (GRAPHS). In brief, GRAPHS is a cluster-randomized cookstove intervention trial in rural Kintampo, Ghana (Jack et al., 2015). Participants were pregnant women who were randomized to receive an improved biomass stove called BioLite (Brooklyn, New York), an LPG stove, or maintain use of their traditional 3-stone fire. Participants in the LPG arm of the study were provided with free LPG fuel for the duration of the study. A sub-cohort of 220 participants were randomly chosen from the BioLite (n = 117/526) and LPG (n = 103/361) arms of GRAPHS for the current study (**Figure 2**). These individuals agreed to have stove use monitors (SUMs) installed on their LPG or BioLite stoves for six months prior to the end of their enrollment in GRAPHS and for an additional six months after their participation in GRAPHS ended. Participants in the LPG arm no longer received free LPG fuel after study termination. Therefore, this study offers a unique opportunity to study potential stove use suspension in the 6 months after GRAPHS ended.

Figure 2: Timeline of GRAPHS and the monitored sub cohort, relative to enrollment into GRAPHS.



Ethical Approvals

Ethical approvals for this study were obtained from the Institutional Review Board of Columbia University Medical Center, and the Kintampo Health Research Centre Institutional Ethics Committee.

Baseline and Process Data Collection

Questionnaires were administered upon enrollment and throughout the GRAPHS study period during weekly visits. Demographic variables used in the current study were captured at baseline. For the analysis, we derived a household asset index, utilized by the World Bank, as a measure of socioeconomic status using a principal components analysis of variables including: type of housing materials, type of toilet facility, primary water source, type of home ownership, household ownership of livestock animals, and household ownership of consumer durables (Gunnsteinsson et al., 2010).

Weekly surveys were administered during GRAPHS, and included stove use questionnaires (**Supplemental Figure 1**). Participants were asked if they used the intervention stove the day preceding the weekly visit (BioLite or LPG). We used these data to summarize intervention stove use throughout the GRAPHS study period. Follow up questions were used to discern reasons for reported non-intervention stove use, including an open-ended question asking why participants had cooked but not with the intervention stove. We utilized text analysis to explore these reported reasons for non-intervention stove use (Silge & Robinson, 2017). Stop words (commonly used articles and prepositions) were removed during pre-processing. Then we generated unique bigrams (verb and/or noun combinations) to offer insight into the sentiment of the short responses (Tan, Wang, & Lee, 2002). We explored bigrams and calculated the relative frequencies of six potential categories for self-reported non-compliance. These categories were not pre-established, but determined by reviewing the data. They were: 1) device breakage, 2) food quantity, e.g. cooking for a larger group, having guests, etc., 3) food types, e.g. stirring, frying, boiling, 4) not home (traveling), 5) speed issues, e.g. being in a hurry, late to work, cooks slowly, and 6) fuel supply, wet or insufficient wood (BioLite) or empty cylinders (LPG). Words that contribute to each category can be found in **Supplementary Table 1**.

Trained field staff conducted surveys in the participant's local language, and documented responses on paper forms. Field supervisors collected and checked all surveys for completeness and accuracy. Office staff then entered data into secure servers at the Kintampo Health Research Centre (KHRC).

Spatial Data and Analysis

Individuals who have more fuelwood available to them may value intervention stoves less due to relative time spent on fuelwood collection (Abadi, Gebrehiwot, Techane, & Nerea, 2017). We test this theory by using remotely sensed tree canopy data as a proxy for fuelwood availability. Remotely-sensed tree canopy data for 2010 were downloaded from the Global Forest Change dataset (Hansen et al., 2013) (see **Supplemental Figure 3**). The data are stored as raster files with a 30-meter resolution, and cells represent proportion of tree cover, defined as canopy closure for vegetation taller than 5 meters. Geocoordinates for study participants were drawn from the Kintampo Demographic and Health Surveillance System (Owusu-Agyei et al., 2012) and were used to create radial spatial buffers from 1 to 4 kilometers. Spatially-weighted averages were calculated within each household's buffers. Summary statistics for the 3-kilometer buffer averages are available in **Supplementary Table 2**. Spearman correlations were then calculated between questionnaire data on self-reported time collecting wood in a week, and the proportion of tree canopy in the buffer.

Stove Use Monitoring & Data Processing

Stove use was tracked with iButton temperature loggers (Maxim Integrated, San Jose, CA, USA) that logged temperature in degrees Celsius every ten minutes (approximately two weeks of logging capacity). Fieldworkers retrieved data every two weeks using Thermodata data downloaders (Thermodata, Eight Mile Plains, QLD, Australia). These downloaders feature a large memory capacity and a 'tap-and-go' approach to downloading, whereby fieldworkers need only hold the downloader to the SUM for a few seconds. Office staff then upload all of the field visit data to the KHRC central servers for later processing.

Raw temperature data was transformed into a 'duration of cooking events' variable using the *AnomalyDetection* package in R. While this package was originally developed to detect anomalies in internet traffic, when applied to temperature data, we have found that the package detects events that deviate from the ambient diurnal temperature pattern. We applied numerous filters to the processing, including only considering positive slope anomalies as cooking time and grouping anomalies within 60 minutes of each other. Stove use was transformed from continuous to categorical, with our outcome measured as a 0 or 1 to stove use in a given week. Because GRAPHS had a rolling enrollment and disenrollment, so dates were transformed from calendar dates to a number of weeks relative to a participant's study end date. The resulting dataset provides an objective sensor-based measure of cookstove use.

Survival Analysis

We leveraged our longitudinal data to perform a survival analysis via a cox proportional hazards regression. The outcome of interest is the first week of suspended use, defined as the week after the last recorded intervention cookstove use during the 12 months of stove use monitoring. Univariate regressions were performed for demographic and household-level characteristics with pre-established associations with stove use (Lewis & Pattanayak, 2012; Puzzolo et al., 2016; Rehfuess et al., 2014). They included: household wealth (asset index), maternal education, maternal independent income, ethnicity, religion (Christian/non-Christian), and fuel collection time. We also included the tree canopy data from our spatial analysis to explore potential ecological drivers of clean/improved cookstove use.

Data Integration & Analyses

We assemble various data types to develop a holistic assessment of impediments and barriers to sustained use, ultimately yielding insights into the factors influencing suspended clean cookstove use. Survey responses during the study period allow us to characterize difficulties encountered while LPG is free and fieldworkers can support use. Survival analyses allow us to identify the factors that inform clean cookstove suspension without free fuel and staff support.

All data analyses were performed in R version 3.5.1. Text analyses were conducted with the *tidytext* package. Spatial analyses were conducted using the *raster* and *sf* packages. Stove use data processing was done with the *AnomalyDetection* package, and survival analyses were performed with the *survival* and *survminer* packages.

Results

Description of the cohort and participants

Table 1 outlines participant characteristics of the entire GRAPHS cohort and the sub cohort of BioLite and LPG users. Sub cohort participants share similar characteristics to the overall GRAPHS cohort. The most notable differences are between the sub cohort arms, where BioLite and LPG users have different proportions of ethnic and religious groups represented. Another notable feature of the entire GRAPHS cohort is that participants had more years of education than their male partners.

Table 1: Demographic and household characteristics of the GRAPHS cohort and the Sub Cohort (BioLite and LPG) tracked with stove use monitors (SUMs).

	GRAPHS Cohort	BioLite	LPG
n	1412	117	103
Household size (mean (std. dev.))	6.54 (3.57)	6.31 (3.1)	5.90 (2.28)
Ethnicity (%)			
Akan	243 (17.2)	22 (18.8)	11 (10.7)
Dagarti	314 (22.2)	19 (16.2)	18 (17.5)
Gonja	217 (15.4)	13 (11.1)	26 (25.2)
Konkonba	192 (13.6)	21 (17.9)	10 (9.7)
Other	446 (31.6)	42 (35.9)	38 (36.9)
Religion (%)			
Christian	864 (61.2)	74 (63.2)	57 (55.3)
Muslim	421 (29.8)	27 (23.1)	41 (39.8)
Other	127 (9.0)	16 (13.7)	5 (4.9)
Marital Status (%)			
Married	777 (55.0)	74 (63.2)	61 (59.2)
Living together, unmarried	458 (32.4)	31 (26.5)	29 (28.2)
Single	177 (12.5)	12 (10.3)	13 (12.6)
Participant’s Years of Education (mean (std. dev.))	4.04 (3.92)	3.96 (3.82)	4.03 (3.94)
Husband/Partner years of Education (mean (std. dev.))	1.68 (1.98)	1.9 (1.96)	1.83 (1.95)
Household Asset Index (mean (std. dev.))	0.00 (1.95)	-0.23 (1.61)	-0.45 (1.41)
Participant’s Age (mean (std. dev.))	29.01 (7.17)	30.11 (6.72)	29.03 (6.76)
Hours per week Collecting Wood (mean (std. dev.))	6.41 (6.43)	5.77 (5.91)	5.02 (5.58)

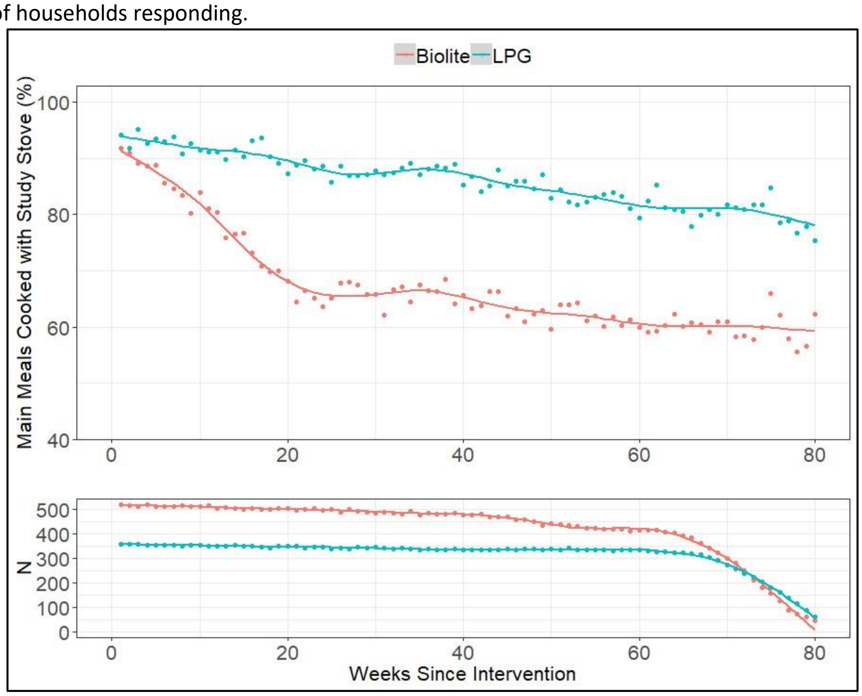
Demographic, Household, and Spatial Relationships in GRAPHS

Variables associated with new cookstove adoption and/or sustained use are likely to be correlated with one another. **Supplemental Figure 2** shows correlations between continuous variables in our cohort; they demonstrated several key relationships. Larger households spent more time collecting firewood (Spearman's ρ = 0.25) and larger households had higher asset indices (ρ = 0.42). Higher asset homes also spent more time collecting wood (ρ = 0.12). Households with a higher proportion of remotely sensed tree canopy within 1 kilometer spent less time collecting firewood (ρ = 0.17).

Self-reported Stove Use

Participants showed differences in self-reported stove use patterns during GRAPHS by arm of study (**Figure 3**). At the beginning of GRAPHS there was near universal stove compliance for both arms. As time progressed, self-reported stove use decreased for each study arm, but more substantially for the BioLite. By the end of GRAPHS, 60% of BioLite study arm participants reported using their stoves for their main meal; whereas at the end of the study, 80% of LPG arm participants report intervention stove use for their main meal.

Figures 3: Weekly self-reported intervention stove use for main meals throughout GRAPHS. Top = proportion reported used. Bottom = Number of households responding.



Self-reported Non-intervention Stove Use

Participants reporting to have used a non-intervention stove (3-stone fire or charcoal) for some meals were asked which foods were cooked in these meals (**Figure 4**). Participants in both study arms reported cooking tuo zaafi (TZ) and fufu with non-intervention stoves in higher proportion than other food types, though this pattern was more pronounced for BioLite rather than LPG users. These are all foods that consist of a pounded and thickened starch, served alongside a soup or stew.

In addition, participants were asked weekly whether they had sustained any burns while cooking with the intervention stoves. Five percent of individuals experienced burns in the LPG arm (N=20), compared to 20% of participants in the BioLite arm and (N=101), nine percent of participants in the control arm (N=45). An analysis of self-reported stove use stratified by burn experience demonstrates that burns are associated with decreased intervention stove use for BioLite (RR: 0.958, p = 0.009),but not LPG users (p=0.975) (**Table 2**).

Figure 4: Foods cooked with non-intervention stoves. *TZ = Tuo Zaafi, Viands = boiled starchy vegetables (cocoyam, plantains, cassava, etc.).* Values do not sum to 100% due to participants who chose not to respond.

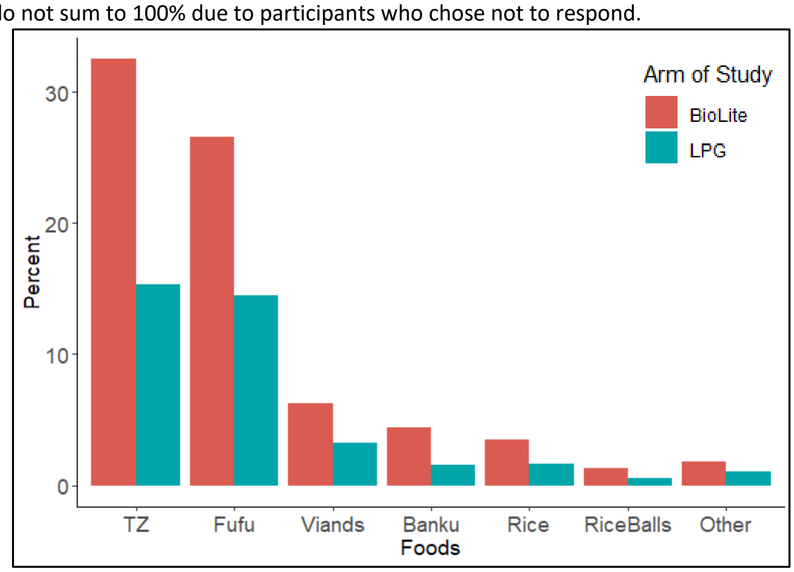
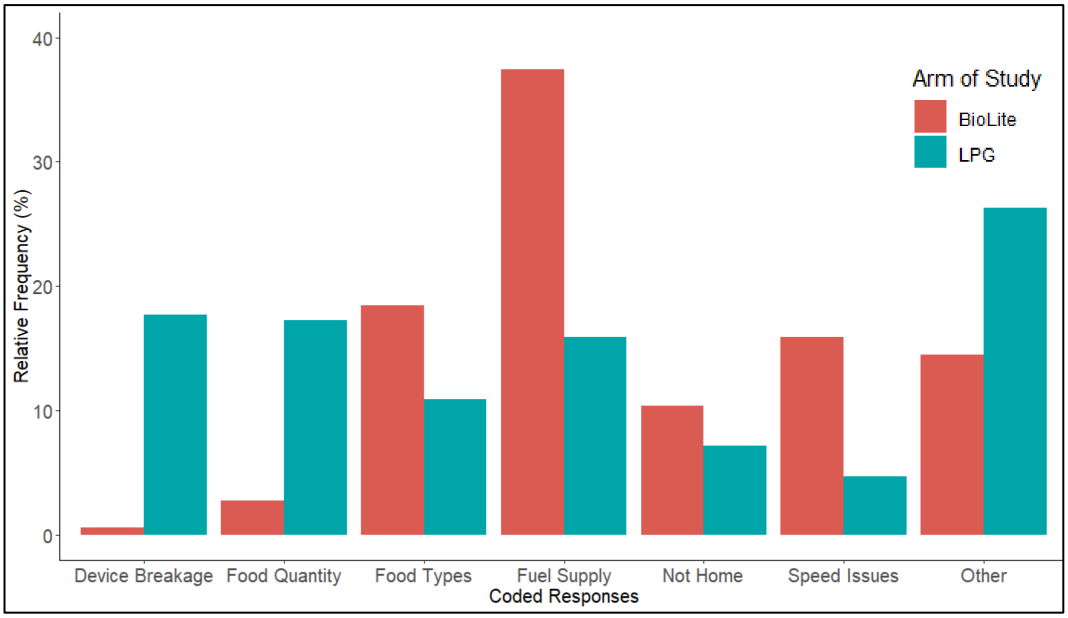


Table 2: Stove use stratified by individuals who report burns from the intervention stove compared to those who report no burns. Rate ratios and p values calculated from a quasi-poisson regression with per person days of use as the dependent variable.

Fuel Type	Burns	Weeks used	Total Weeks	Proportion Use	Risk Ratio	P value
LPG	No Burns	20232	23298	86.8%	Reference	0.009
	Burned	1204	1461	82.4%	0.958	
BioLite	No Burns	18621	26945	69.1%	Reference	0.975
	Burned	4389	6590	66.6%	**1.001**	

Text analysis of reasons for non-intervention stove use yielded different patterns for LPG (**Supplemental Figure 4**) and BioLite (**Supplemental Figure 5**). Bigrams formed from open-ended responses were grouped into six themes (**Figure 5**). Device breakage was mentioned in 18% of bigrams from LPG users, but only in 1% of BioLite bigrams. For LPG users, stove breakages included faulty regulators, leaking gas, or broken tubes. Food quantity was also a prevalent concern, mentioned in 17% of LPG bigrams and 3% of BioLite bigrams. Here, individuals may have been cooking for more than their immediate family in a social gathering like a funeral or for farm laborers. As mentioned above, specific food types on intervention stoves was a concern for both intervention study arms. Using the text analysis we were able to capture more than the specific food types, but also preparation styles that women find difficult with the stoves. For example, frying and stirring are commonly reported difficulties with intervention stoves. Difficulties with fuel supply refers to access challenges for intervention stove fuels. In the case of BioLite, almost 40% of bigrams mention a fuel supply issue, including firewood shortage, wet firewood, or not having wood pieces that were small enough for the intervention stove. We also found that travel or sleeping elsewhere was a consistent reason for non-intervention stove use. In these circumstances, women were without access to the intervention stove. For example, study participants report sometimes sleeping at farm plots that are remote from their primary home and intervention stove. Finally, many women reported getting home late, leaving the home early, or otherwise being in a hurry as reasons not to cook with the stove. We referred to these reports as speed issues, and found that 16% of BioLite and 5% of LPG bigrams mention such challenges.

Figure 5: Results of text analysis from open-response question regarding reasons for not using intervention stoves in the past week. Synthesized from bigrams depicted in Supplemental Figures 4 and 5. Words categorizations in Supplemental Table 1.



Tree canopy and self-reported fuelwood collection time

For all buffer distances, we observed a negative association between participants' weekly self-reported firewood collection time and the overall proportion of tree canopy within various radial buffers of their home (used as a proxy for biomass access). Therefore, when there was a lower proportion of tree canopy in a participant's buffer, they report a higher weekly firewood collection time (**Table 3**). The magnitude of the association is largest at the 3-kilometer buffer (ρ = -0.191).

Table 3: Correlations for weekly self-reported firewood collection time and proportion of tree canopy within a given distance of the participant's home (N = 1412)

Buffer Size	Spearman's rho	p-value
1 km	-0.170	<0.001
2 km	-0.185	<0.001
3 km	-0.191	<0.001
4 km	-0.184	<0.001

Stove use monitoring for the sub-cohort

Participants' stove use was tracked via SUMs in the final 6 months of GRAPHS and 6 months after study closeout to understand patterns of suspended intervention stove use. **Figure 6** shows the proportion of participants with measured intervention stove use (per SUMs) in a given week relative to each individual's study termination date. During GRAPHS, the LPG arm was provided with free LPG refills. We intuited that LPG use would decrease substantially after the study terminated, which is supported by these results. However, we found that LPG use seemed to begin declining before the actual study termination date. BioLite use was consistently lower than LPG before GRAPHS closeout. After GRAPHS closeout, BioLite use was consistently higher than LPG use. Stove use also varied seasonally (**Figure 7**). BioLite users appeared to use their stoves more during the non-Harmattan/wet season (62 minutes/week) compared to the Harmattan (49 minutes/week). This trend was more pronounced for LPG participants, who used their stoves less during the non-Harmattan (107 minutes/week) than the Harmattan (61 minutes/week). There was also evidence a bi-modal distribution of stove use for both stoves (**Supplemental Figure 6**). Both stoves have a lower mode of 10 minutes per week, which is the lowest detectable stove use given the device sampling frequency. The higher mode for BioLite was 120 minutes per week and 230 minutes for LPG. There is also a mode at zero, implying those who did not use their stoves on given days or had already suspended stove use.

Figure 6: Proportion of measured stove use (from stove use monitors) in a given week relative to the GRAPHS study end date

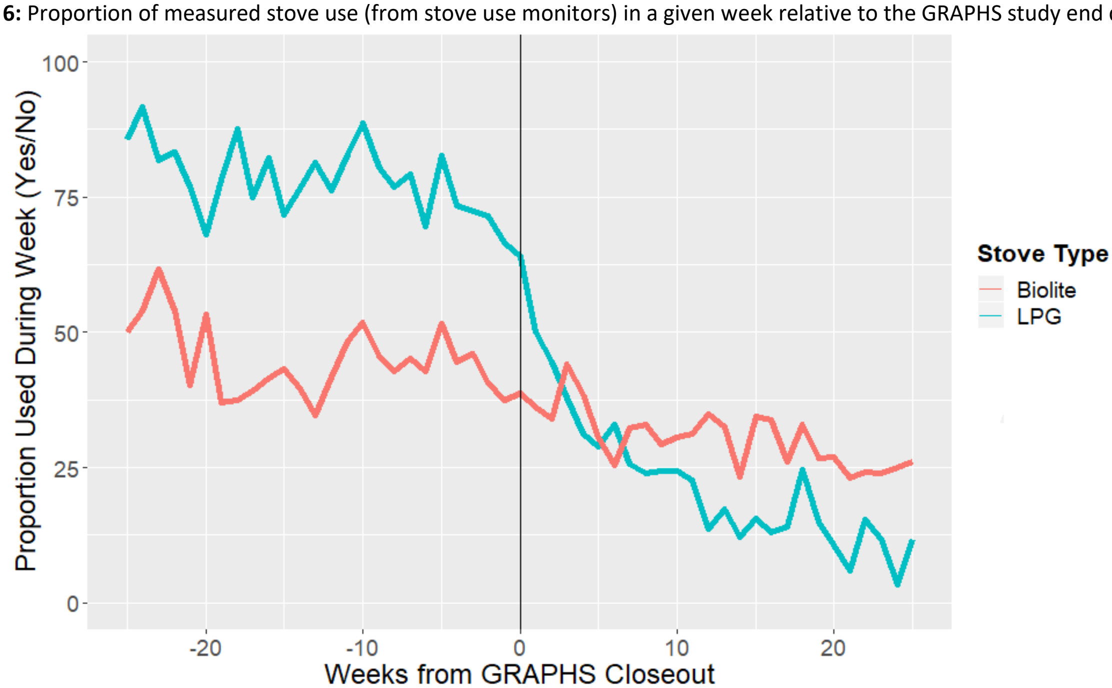
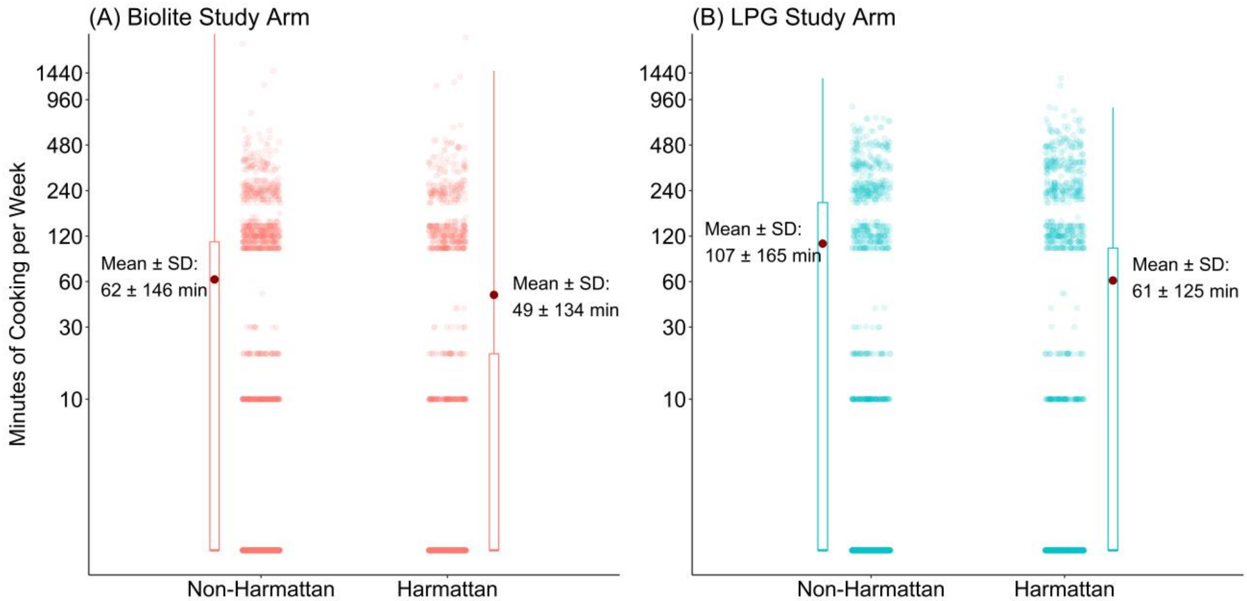


Figure 7: Mean stove use in the sub-cohort by stove and season. Red point = mean, dots = observations of minutes cooking per week. Median of each group = 0 minutes.



Univariable Cox Regressions

We conducted univariable cox proportional hazard regressions for LPG users to understand the relationships between household, demographic, and ecological variables and the suspension of stove use for the LPG sub cohort (**Figure 8**). We focus on LPG due to the high use during GRAPHS compared to BioLite. The survival analysis starts at 6 months prior to the end of each participant's enrollment in GRAPHS and continues for 6 months following the GRAPHS study end (**Supplemental Figure 8**). The only statistically significant variable was for individuals above the median proportion (19%) of tree canopy in their 3-kilometer buffer ($HR_{unadjusted}$ = -0.58, p < 0.001). This means that those with above median tree canopy were less likely to suspend use of the LPG stove by the end of the study compared to those with below median tree canopy. Statistical significance persisted and the magnitude strengthened when adjusted for potential confounders like the asset index, household size, and participant's occupation (farmer versus not) ($HR_{adjusted}$=-0.646, p = 0.007). **Figure 9** demonstrates the differences in suspended use between the high tree canopy and low tree canopy homes at the 3-kilometer buffer. The median survival time for those above the median tree canopy was 37 weeks while those below was 29.5 weeks.

Figure 8: Univariable cox proportional hazard regression coefficients: Hazard ratios with 95% confidence intervals. Outcome is stove use suspension (week after last measured use). n = 103.

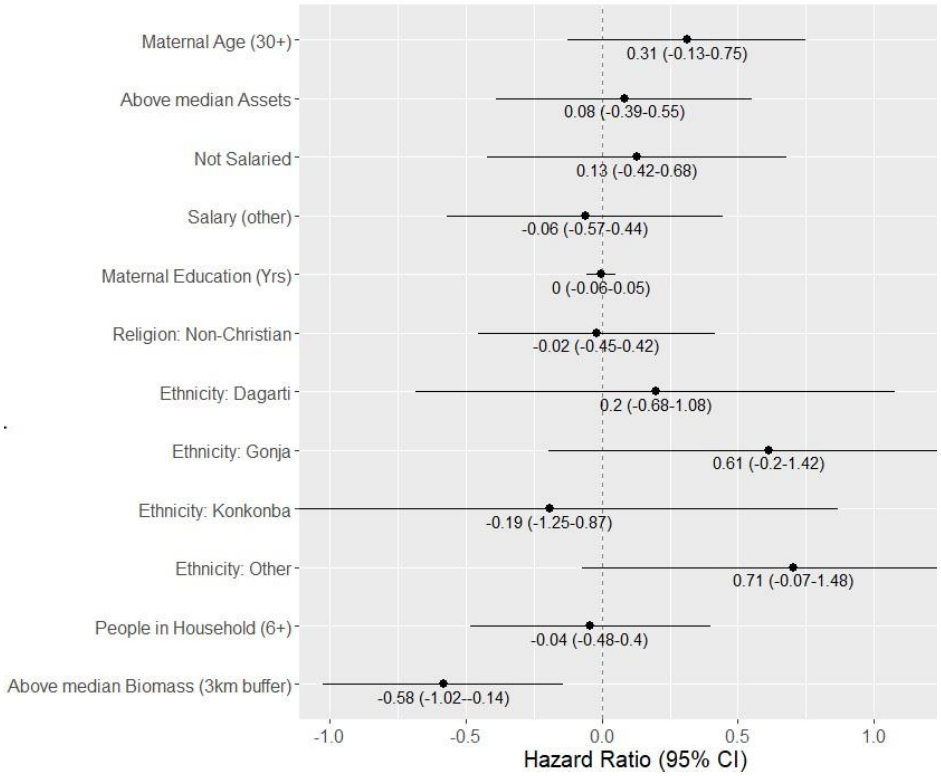
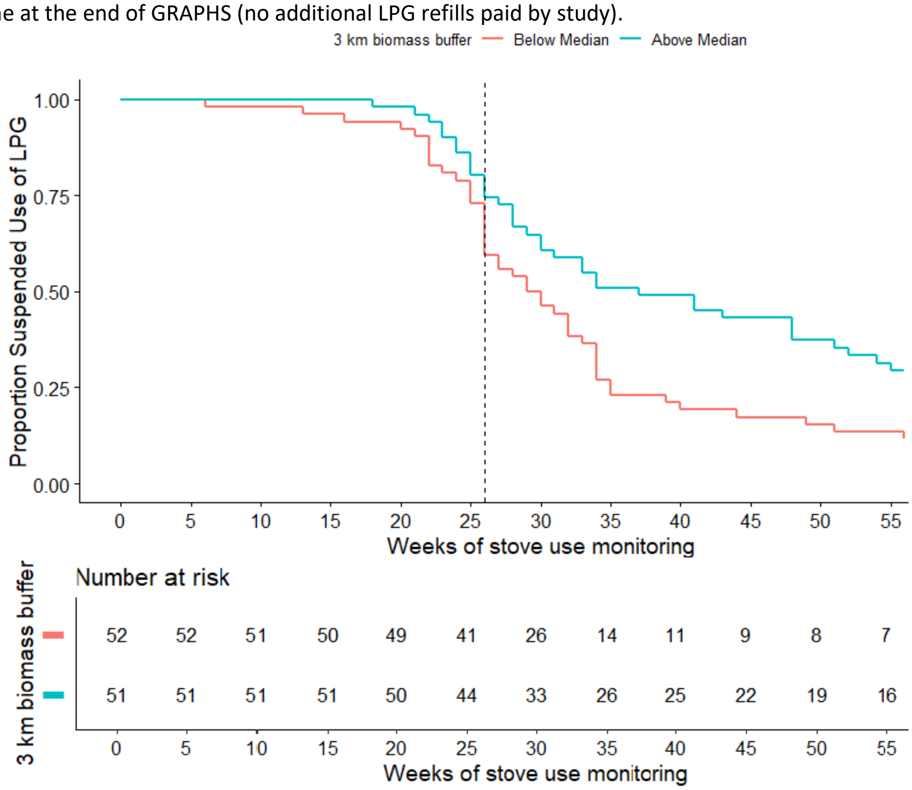


Figure 9: Survival curve comparing suspended use of LPG for those above the median tree canopy in a 3-kilometer buffer, and below. Dashed line at the end of GRAPHS (no additional LPG refills paid by study).



Discussion

We conducted a study in a rural area of Ghana with robust longitudinal data from surveys and sensors to analyze 1) patterns of stove use by study arm and potential impediments of use, and 2) the factors related to suspended clean cookstove use. Our analysis suggests that particular foods are not preferred on improved or clean cookstoves, namely TZ, fufu, and starchy vegetables. We also found that fuel wood collection time is negatively associated with proportion of tree canopy, with the highest correlation within a 3-kilometer buffer. When focusing on the particular factors of suspended clean cookstove use, we found that tree canopy within a household's buffer is the only significant predictor of stove use duration. Contrary to our hypothesis, high tree canopy was protective, meaning that those in high tree canopy areas were more likely to sustain rather than suspend use by the end of the study. This relationship persisted when adjusted for potential confounders like wealth or occupation.

Our research supports findings from past studies that stoves may be perceived as more or less suitable for different types of cooking tasks (Dickinson et al., 2019; Gould & Urpelainen, 2018; Grimsby, Rajabu, & Treiber, 2016; Hollada et al., 2017; Piedrahita et al., 2016). This is valuable information given that foods are culturally specific, and interventions should be considered accordingly. In this case, traditional Ghanaian cuisine includes thick starchy foods that accompany stews, such as banku, fufu, and tuo zaafi. These dishes require constant stirring over a fire. It is possible that individuals prioritize the intervention stoves for faster, lower-intensity dishes, in order to maximize limited supplies of LPG. Alternatively, participants may not know how to how to prepare these meals with BioLite or LPG stoves. Given the required movement of the foods, this could result in mistakes in preparation and handling, resulting in accidental burns. We found that only 5.5% of LPG users experienced burns. Even more BioLite users reported burns, in fact higher than traditional 3-stone fire users. Although improved and traditional cookstoves are seen as a means of reducing burns (Simon, Bailis, Baumgartner, Hyman, & Laurent, 2014), this does not negate that a burn from an intervention stove could deter future use.

Further, it is notable that the largest burn difference was between intervention stoves, whereby LPG users experienced the least and BioLite experienced the most.

Text analysis allowed us to explore additional reasons for use of non-intervention stoves that were not captured by structured survey questions. We found that the most common reasons for use of non-intervention stoves among LPG participants were device breakage and food quantity. Device breakage concerns could be partially reflective of fears regarding the safety of LPG, which researchers have found in other parts of the world (Budya & Yasir Arofat, 2011; Kimemia & Annegarn, 2016). BioLite users most commonly discussed fuel supply concerns. This finding would seemingly be applicable to traditional stove users as well, given that BioLite still uses biomass fuel sources. Our interpretation is that individuals would use stored or purchased charcoal in these cases, as it is the most common secondary fuel in this region (Van Vliet et al., 2013). Many BioLite users report fuel supply issues due to wet wood. Since rain is largely seasonal in this region, it is probable that these concerns were mostly a product of the non-Harmattan/wet season. We found stark stove use differences for LPG and BioLite where use was higher in the wet season. Research elsewhere demonstrates seasonal stove use patterns (Lam et al., 2017). These technologies are more mobile than 3-stone fires, so it may be that individuals appreciate the ability to bring them indoors during the rains. It is also possible that participants can afford to refill their stoves during the harvest season, rather than the leaner Harmattan/dry season.

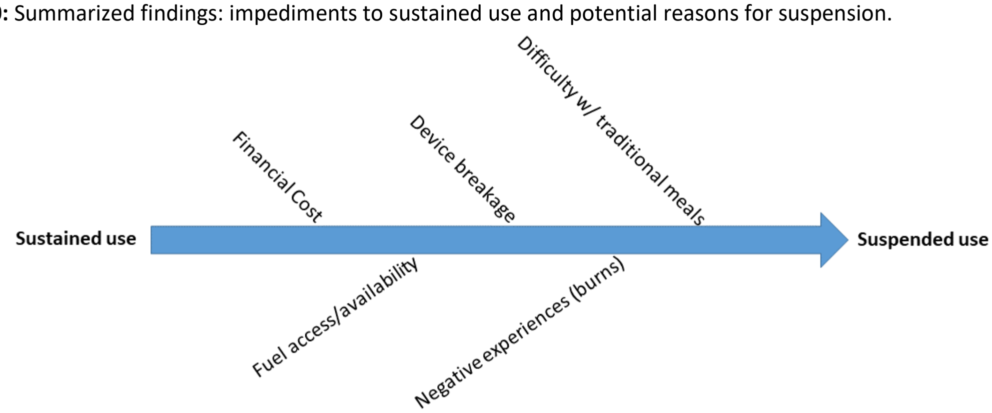
The findings from our spatial analysis demonstrate that remotely sensed datasets may be useful for inferring fuelwood collection time, demonstrating the highest magnitude relationship at a 3-kilometer buffer. This may indicate the furthest average distance that individuals are willing to travel for fuelwood in this region. Our survival analysis indicates that individuals with high biomass availability are more likely to sustain use of LPG. We initially believed that higher biomass availability would yield higher suspended use. However, self-reported stove use data indicate that LPG participants had high overall intervention stove use. Recent qualitative evidence bolsters that individuals in this cohort like the LPG stoves (Agbokey et al., 2019). In a situation where individuals no longer have access to free LPG refills, they may be more likely to stove stack (concurrently use traditional stove types) in order to extend the LPG. We initially intended to measure traditional cookstove use in tandem with intervention stoves in order to assess household stove stacking. However, device failures and consequent data loss means we were unable to measure and analyze this as a possible explanation.

There were several limitations to our analysis. First, we were unable to assess the degree of stove stacking. For the health benefits of clean cookstove adoption, it is imperative that we decrease stove stacking *and* suspension of clean cookstoves. Second, while our remotely sensed dataset offers a precise estimate of tree canopy cover in a fine spatial resolution, it may not completely serve the underlying data need. While it is possible that individuals travel into dense bush to collect wood, it is more likely that they travel along forest edge, where smaller and more accessible biomass exists. This dataset cannot be used to identify forest edge. Furthermore, distance to biomass is a simple construct, and past studies have shown that more complicated dynamics are likely (Brouwer, Hoorweg, & van Liere, 1997; Köhlin, Parks, Barbier, & Burgess, 2001). Our measure of access was based on a radial buffer from the home, and evidence from India shows that individuals are unlikely to travel in such symmetrical patterns (Singh, Aung, & Zerriffi, 2018). Future studies should consider the actual source of biomass, individual access to purchasing charcoal or fuelwood, and collection of wood reserves. A third limitation is our lack of survey data in the post-GRAPHS time period. Fourth, while we have a measure of wealth among our cohort with our constructed asset index, we lack a measure of income. Income changes over time, and those fluctuations could be instructive in understanding reasons for suspended cookstove use. This is especially true in an agricultural setting where income is often seasonal. Suspended use studies should consider ways to measure income amongst participants over time. Finally, we suggest that intervention stoves may be more suitable for some meals rather than others. It is possible that this relationship is confounded by a third, unobserved variable.

To our knowledge, our study is the first to employ a framework specifically focusing on suspension of clean cookstove use. We do so utilizing data from a rich longitudinal cohort. The analysis also uses remotely sensed data as an objective, publicly available dataset with worldwide coverage as a method for determining biomass availability. If proven to inform clean cookstove sustained and/or suspended use, these datasets can be leveraged as part of national cooking policies to target behavioral and/or policy interventions. Combined with demographic surveillance datasets, such efforts would require little surveying or primary data collection. Finally, our use of stove use monitors over an extended time period should overcome the potential of social desirability bias compared to survey responses (Wilson et al., 2015).

Conclusions and policy implications

Figure 10: Summarized findings: impediments to sustained use and potential reasons for suspension.



This study probes important areas of clean cookstove sustained and suspended use in rural Ghana. Our findings suggest that additional efforts should be made to understand the role of biomass availability on suspended stove use. This is particularly germane in a region with deforestation concerns. Evidence suggests LPG fuels are widely accepted, but cost may be prohibitive. Additionally, individuals may not know how to prepare traditional meals on LPG stoves, or how to repair stoves when broken.

These seemingly small events can precipitate into stove use suspension (**Figure 10**). Without additional efforts, individuals may continue to suspend use and even abandon their stoves altogether.

Given the known exposure reduction limitations of biomass fuels, and current Ghanaian policy towards scaling LPG use, we focus our recommendations on LPG instead of improved cookstoves. Our past research has shown that efforts to scale LPG in Ghana have been more successful in urban than rural areas (Asante et al., 2018). Aware of this issue, Ghana has a Rural LPG Promotion Program that freely distributes LPG stoves and cylinders. Ghana is also undergoing major overhaul of the LPG distribution model (NPA, 2017). The country is moving from individual cylinder ownership to a cylinder recirculation model (Adogla-Bessa, 2019). This policy change has the potential to directly improve LPG fuel access in rural areas. Refueled LPG cylinders could be distributed closer to rural end-users. We recommend those vendors also maintain a small supply of LPG stove parts, which could support those with stove breakage concerns.

The Rural LPG Programme performs a sensitization process during community distribution of LPG stoves (Abdulai et al., 2018). This sensitization includes presentation of the health and ecological risks of using biomass fuels, and the benefits of LPG. We believe that these community sensitizations have the opportunity to draw more explicitly from behavior change methods. Specifically, they should address the appropriateness of LPG stoves for traditional meals, perhaps through cooking demonstrations. We are testing this approach in Kintampo, results forthcoming (Carrión et al., 2018).

Household financial constraints continue to be a challenge for LPG uptake in many parts of the world (Muller & Yan, 2018). However, Ghana once had a subsidy to reduce this barrier (Mensah & Adu, 2015). This subsidy was removed due to commercial exploitation, i.e. retrofitting commercial vehicles to run on LPG (Biscoff, Akple, Turkson, & Klomegah, 2012). We believe that the cylinder recirculation model offers an opportunity for adapted and controlled reintroduction of the subsidy. By subsidizing cylinders rather than fuel, policymakers can increase confidence that the end use is cooking. Together these recommendations would decrease barriers for sustained use, thus decreasing exposures to household air pollution and the associated disease burdens.

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Supplemental Materials

Supplemental Figure 1: Weekly stove compliance survey questions administered for all participants during the Ghana Randomized Air Pollution and Health Study (GRAPHS).

Which stove did you use to cook your main meal yesterday?

1. 3-stone	2. LPG	3. BioLite	4. Coal pot	5. Other specify: ....

Since my last visit, have you cooked but did not use the intervention stove?.......................... | 1. Yes | 2. No |

If yes then, why?... ....

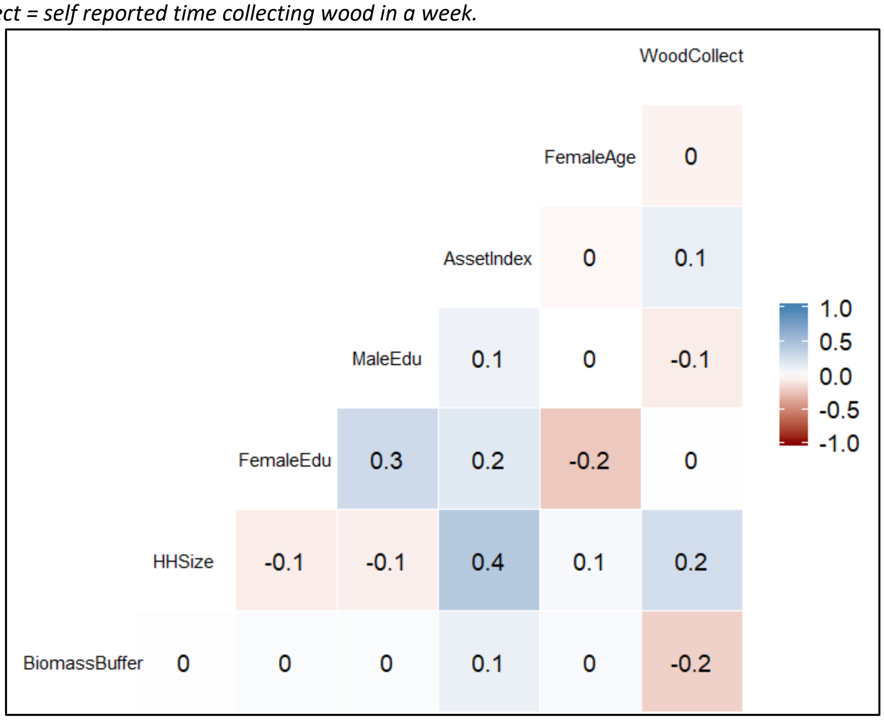
Since my last visit, what meal (s) did you cook but not with the intervention stove? *[Enter 00 if never happened]*.. 1...................................... 2...................................... 3......................................

In the past week, have you been burned while cooking?.. | 1. Yes | 2. No |

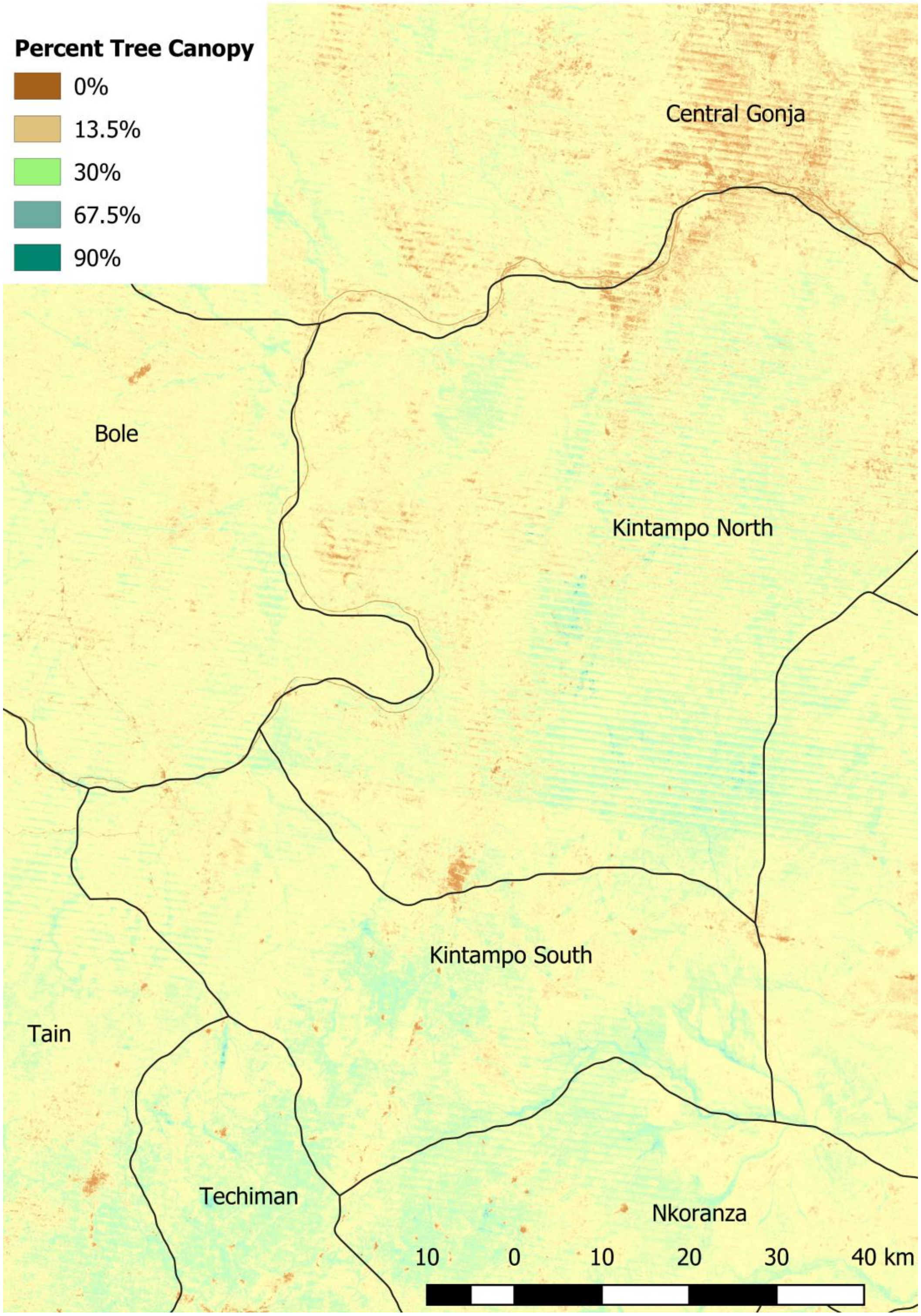
Supplemental Table 1: Words that contribute to bigram analysis categorization.

Category	**Stove Type**	**Words**
Device breakage	LPG & BioLite	Spoil, spoiled, spoilt, broken, broke, damaged, damage, regulator, leak, leaked, faulty
Food type	LPG & BioLite	TZ, banku, fufu, porridge, coco, koko, fry, boil, boiled, boiling, kenkey, stir, stirring, yam, frying, smoking, smoke, bofrot, pito, beans
Food quantity	LPG & BioLite	People, plenty, visitors, quantity, large, commercial, sell, size, sale, guest, guests
Fuel Supply	LPG	Shortage, fetch, empty, cylinder, spent, refill, refilling, finish, finished
	BioLite	Shortage, wet, dry, fetch, firewood
Not Home	LPG & BioLite	Away, farm, travel, traveling, travelled, left, leaving
Speed issues	LPG & BioLite	Slow, fast, hurry, late

Supplemental Figure 2: Spearman correlation plot for GRAPHS Cohort for variables thought to be associated with clean cookstove and improved cookstove sustained use (N = 1412). *Abbreviations: BiomassBuffer = proportion of tree canopy in a 1 km buffer; HHSize = # of individuals living in the home; FemaleEdu = woman's education (years); MaleEdu = man's education (years); WoodCollect = self reported time collecting wood in a week.*



Supplemental Figure 3: Tree canopy in the study region in 2010 with administrative boundaries overlaid.

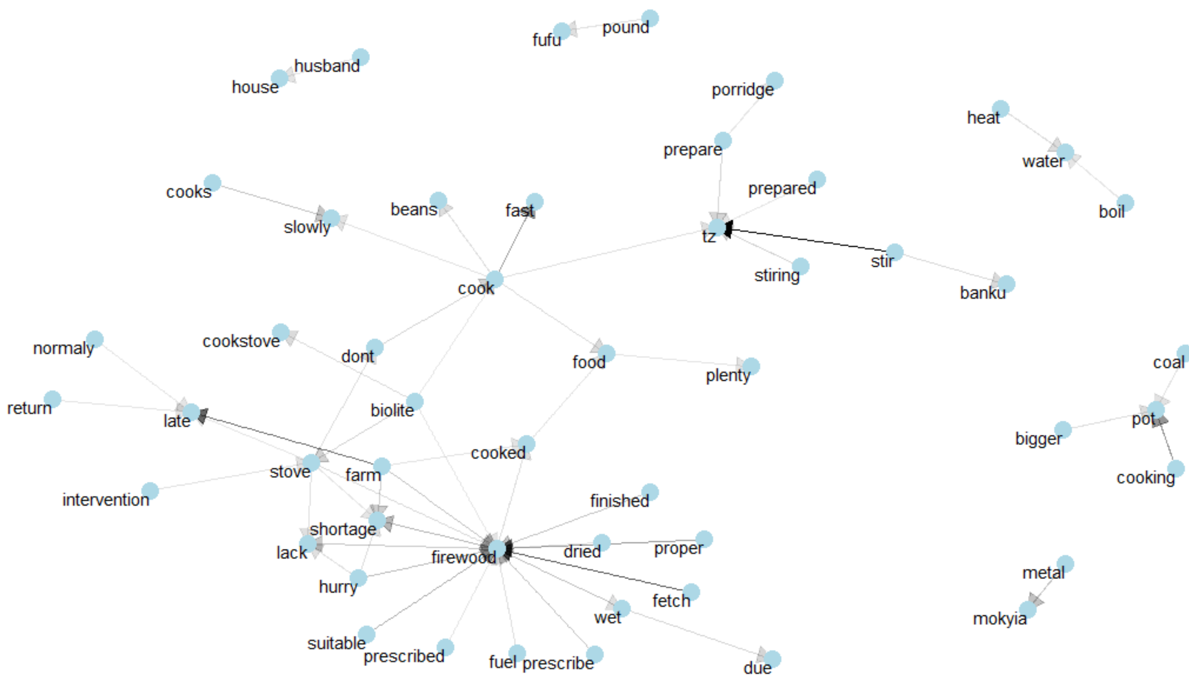


Source: Hansen/UMD/Google/USGS/NASA

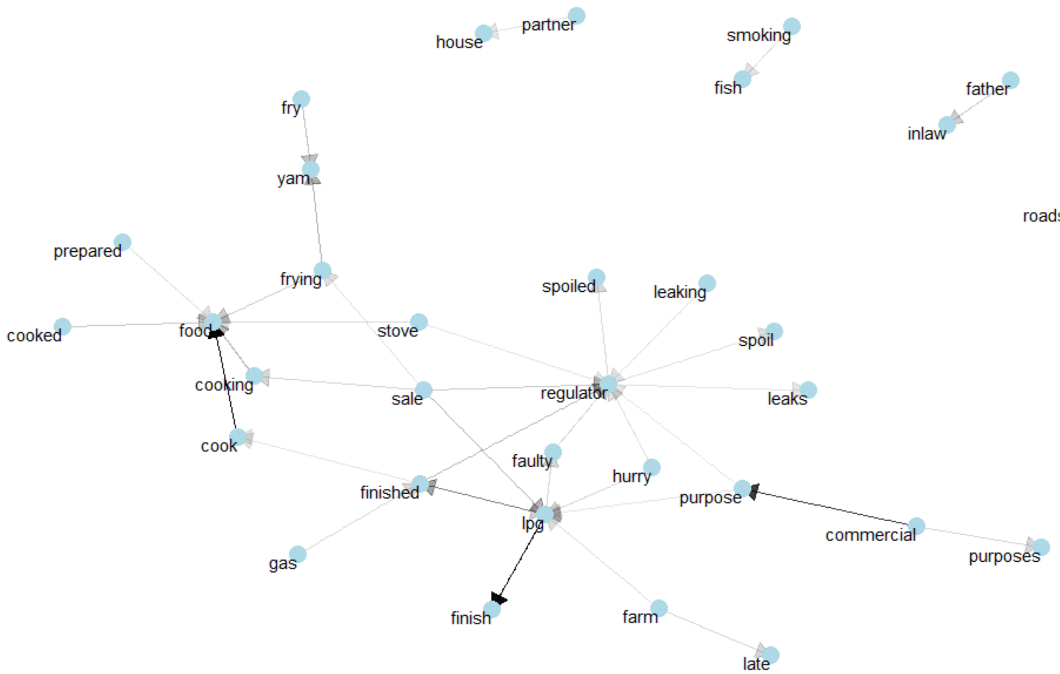
Supplemental Table 2: Summary statistics on 3-kilometer buffer tree canopy in cohort.

Group (n)	Mean (std. dev.)	Median	IQR	Range
GRAPHS Cohort (1412)	20.58% (4.92)	19.58%	18.2-22.8%	10.8-31.4%
Biolite (526)	21.2% (5.55)	19.6%	18.9-23.9%	11.5-31.4%
LPG (361)	19.4% (5.53)	19.2%	18.1-21.2%	10.8-31.4%
3 stone (525)	20.8% (3.46)	20.2%	18.2-22.7%	16.1-29%

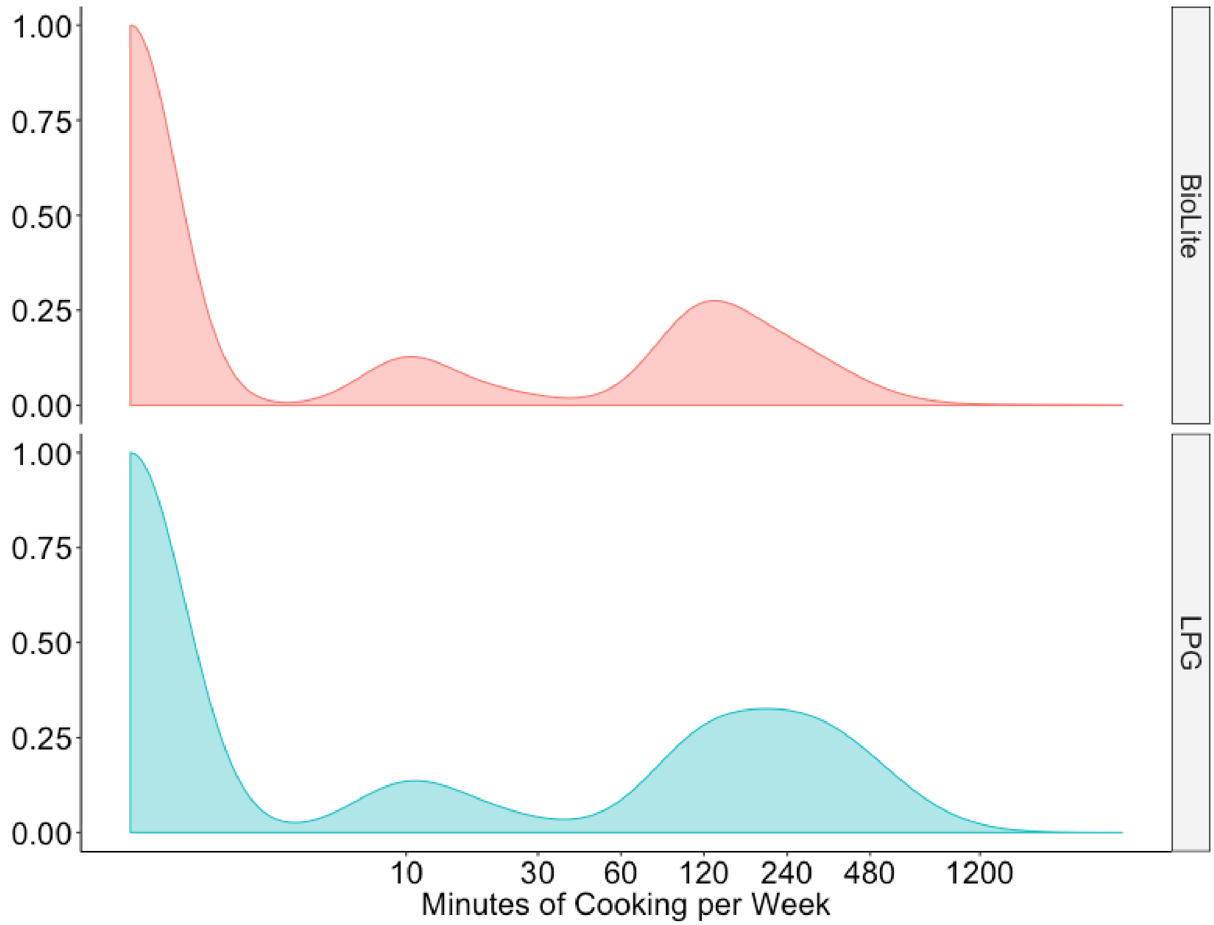
Supplemental Figure 4: Bigrams produced from BioLite participant open responses for reasons why they used a non-intervention stove during the past week. Identified in 5 or more responses. Arrows point from words that are more likely to be the first word in a bigram.



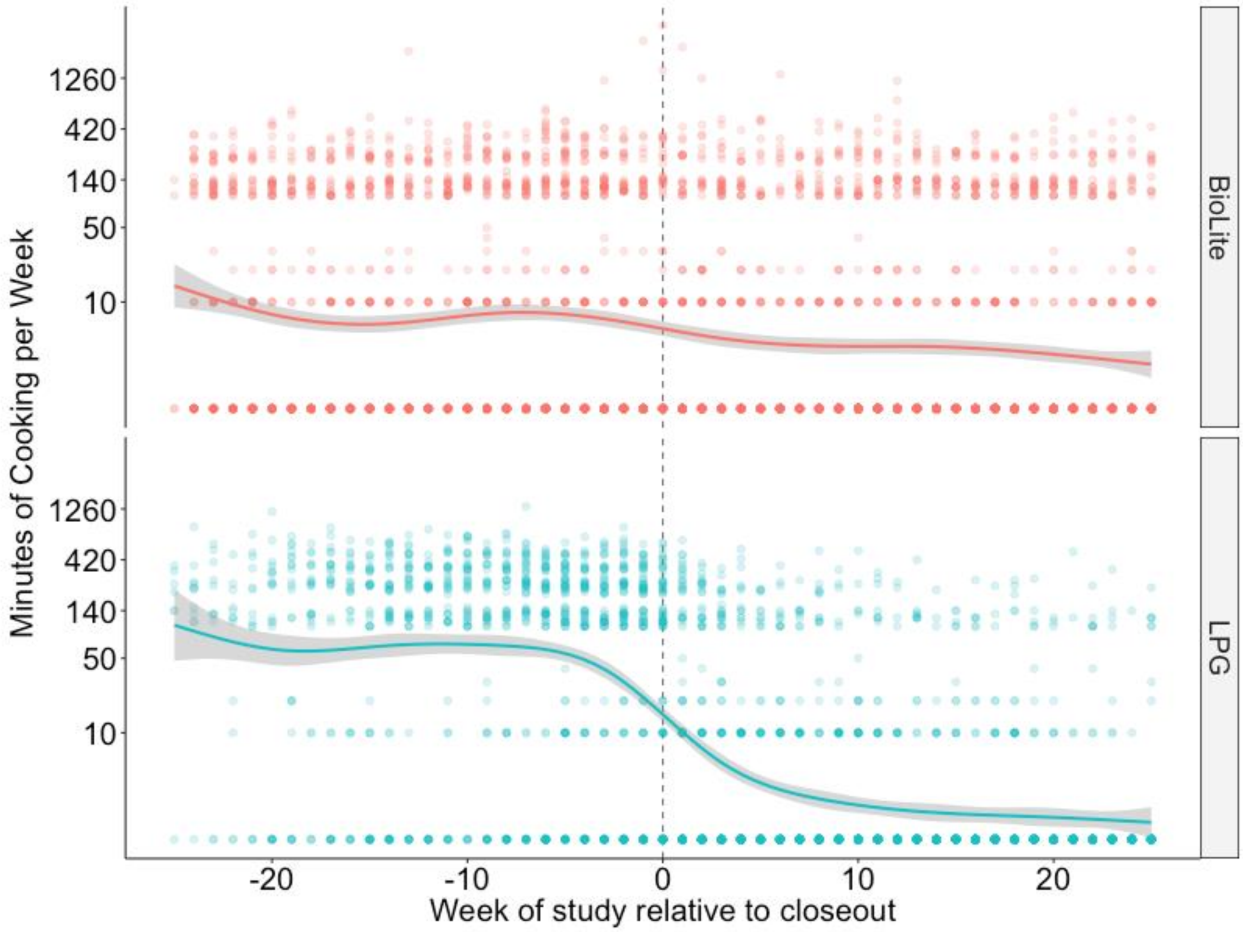
Supplemental Figure 5: Bigrams produced from LPG participant open responses for reasons why they used a non-intervention stove during the past week. Identified in 5 or more responses. Arrows point from words that are more likely to be the first word in a bigram.



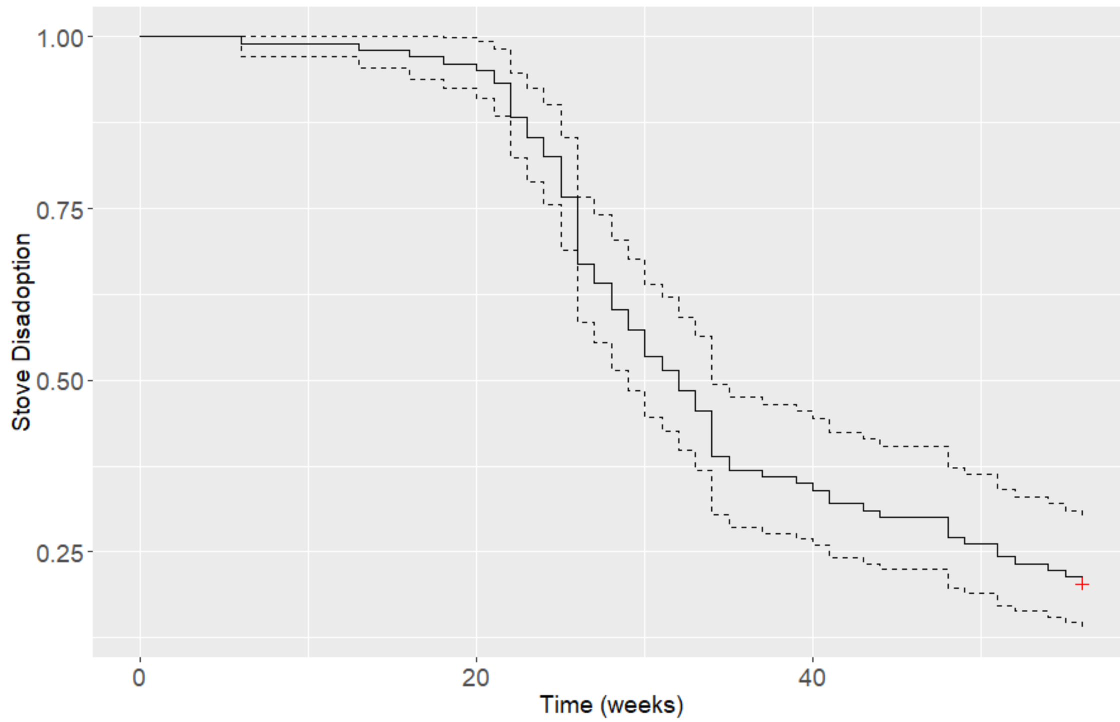
Supplemental Figure 6: Density plot of stove use monitor data (GRAPHS sub-cohort) from BioLite (n=117) and LPG (n=103) participants.



Supplemental Figure 7: Stove use monitoring data for BioLite (n = 117) and LPG (n = 103) participants. The x-axis represents the time to and from the GRAPHS end date. The dots are household weekly observations, and the smoothed line is a local regression curve.



Supplemental Figures 8: Unadjusted survival curve for LPG users (n = 103). The starting point represents 6 months prior to GRAPHS closeout.



References

Abadi, N., Gebrehiwot, K., Techane, A., & Nerea, H. (2017). Links between biogas technology adoption and health status of households in rural Tigray, Northern Ethiopia. *Energy Policy*, *101*, 284–292. https://doi.org/10.1016/j.enpol.2016.11.015

Abdulai, M. A., Afari-Asiedu, S., Carrion, D., Ae-Ngibise, K. A., Gyaase, S., Mohammed, M., … Jack, D. (2018). Experiences with the Mass Distribution of LPG Stoves in Rural Communities of Ghana. *EcoHealth*, *15*(4), 757–767. https://doi.org/10.1007/s10393-018-1369-7

Adogla-Bessa, D. (2019, March 11). Five companies to start Cylinder Recirculation Model - NPA. *Citi Newsroom*. Retrieved from https://citinewsroom.com/2019/03/11/five-companies-to-start-cylinder-recirculation-model-npa/

Agbokey, F., Dwommoh, R., Tawiah, T., Ae-Ngibise, K., Mujtaba, M., Carrion, D., … Jack, D. (2019). Determining the Enablers and Barriers for the Adoption of Clean Cookstoves in the Middle Belt of Ghana—A Qualitative Study. *International Journal of Environmental Research and Public Health*, *16*(7), 1207. https://doi.org/10.3390/ijerph16071207

Asante, K. P., Afari-Asiedu, S., Abdulai, M. A., Dalaba, M. A., Carrión, D., Dickinson, K. L., … Jack, D. W. (2018). Ghana's rural liquefied petroleum gas program scale up: A case study. *Energy for Sustainable Development*, *46*, 94–102. https://doi.org/10.1016/j.esd.2018.06.010

Bailis, R., Drigo, R., Ghilardi, A., & Masera, O. (2015). The carbon footprint of traditional woodfuels. *Nature Climate Change*, *5*(3), 266.

Biscoff, R., Akple, M., Turkson, R., & Klomegah, W. (2012). Scenario of the emerging shift from gasoline to LPG fuelled cars in Ghana: A case study in Ho Municipality, Volta Region. *Energy Policy*, *44*, 354–361. https://doi.org/10.1016/j.enpol.2012.02.001

Brouwer, I. D., Hoorweg, J. C., & van Liere, M. J. (1997). When households run out of fuel: Responses of rural households to decreasing fuelwood availability, Ntcheu District, Malawi. *World Development*, *25*(2), 255–266. https://doi.org/10.1016/S0305-750X(96)00100-3

Budya, H., & Yasir Arofat, M. (2011). Providing cleaner energy access in Indonesia through the megaproject of kerosene conversion to LPG. *Energy Policy*, *39*(12), 7575–7586. https://doi.org/10.1016/j.enpol.2011.02.061

Carrión, D., Dwommoh, R., Tawiah, T., Agyei, O., Agbokey, F., Twumasi, M., … Asante, K. P. (2018). Enhancing LPG adoption in Ghana (ELAG): a factorial cluster-randomized controlled trial to Enhance LPG Adoption & Sustained use. *BMC Public Health*, *18*(1), 689. https://doi.org/10.1186/s12889-018-5622-3

Chalise, N., Kumar, P., Priyadarshini, P., & Yadama, G. N. (2018). Dynamics of sustained use and abandonment of clean cooking systems: lessons from rural India. *Environmental Research Letters*, *13*(3), 035010. https://doi.org/10.1088/1748-9326/aab0af

Di Noia, J., & Prochaska, J. O. (2010). Dietary stages of change and decisional balance: a meta-analytic review. *American Journal of Health Behavior*, *34*(5), 618–632.

Dickinson, K. L., Piedrahita, R., Coffey, E. R., Kanyomse, E., Alirigia, R., Molnar, T., … Wiedinmyer, C. (2019). Adoption of improved biomass stoves and stove/fuel stacking in the REACCTING intervention study in Northern Ghana. *Energy Policy*, *130*, 361–374. https://doi.org/10.1016/j.enpol.2018.12.007

ENERGIA. (2015, September 28). *LPG: Increasing the energy options benefitting women worldwide*. Retrieved from https://www.energia.org/latest-energia-news-lpg-increasing-the-energy-options-benefitting-women-worldwide/

Energy-Commission. (2012). *Ghana sustainable energy for all action plan.* Retrieved from http://energycom.gov.gh/files/SE4ALL-GHANA%20ACTION%20PLAN.pdf

Gould, C. F., & Urpelainen, J. (2018). LPG as a clean cooking fuel: Adoption, use, and impact in rural India. *Energy Policy*, *122*, 395–408. https://doi.org/10.1016/j.enpol.2018.07.042

Grimsby, L. K., Rajabu, H. M., & Treiber, M. U. (2016). Multiple biomass fuels and improved cook stoves from Tanzania assessed with the Water Boiling Test. *Sustainable Energy Technologies and Assessments*, *14*, 63–73. https://doi.org/10.1016/j.seta.2016.01.004

Gunnsteinsson, S., Labrique, A. B., West, K. P., Christian, P., Mehra, S., Shamim, A. A., … Klemm, R. D. (2010). Constructing Indices of Rural Living Standards in Northwestern Bangladesh. *Journal of Health, Population and Nutrition*, *28*(5). https://doi.org/10.3329/jhpn.v28i5.6160

Hanna, R., Duflo, E., & Greenstone, M. (2016). Up in Smoke: The Influence of Household Behavior on the Long-Run Impact of Improved Cooking Stoves. *American Economic Journal: Economic Policy*, *8*(1), 80–114.

Hansen, M. C., Potapov, P. V., Moore, R., Hancher, M., Turubanova, S. A., Tyukavina, A., … Townshend, J. R. G. (2013). High-Resolution Global Maps of 21st-Century Forest Cover Change. *Science*, *342*(6160), 850–853. https://doi.org/10.1126/science.1244693

Hollada, J., Williams, K., Miele, C., Danz, D., Harvey, S., & Checkley, W. (2017). Perceptions of Improved Biomass and Liquefied Petroleum Gas Stoves in Puno, Peru: Implications for Promoting Sustained and Exclusive Adoption of Clean Cooking Technologies. *International Journal of Environmental Research and Public Health*, *14*(2), 182. https://doi.org/10.3390/ijerph14020182

Jack, D. W., Asante, K. P., Wylie, B. J., Chillrud, S. N., Whyatt, R. M., Quinn, A. K., … Mujtaba, M. (2015). Ghana randomized air pollution and health study (GRAPHS): study protocol for a randomized controlled trial. *Trials*, *16*(1), 420.

Johnson, M. A., & Chiang, R. A. (2015). Quantitative Guidance for Stove Usage and Performance to Achieve Health and Environmental Targets. *Environmental Health Perspectives*. https://doi.org/10.1289/ehp.1408681

Kimemia, D., & Annegarn, H. (2016). Domestic LPG interventions in South Africa: Challenges and lessons. *Energy Policy*, *93*, 150–156. https://doi.org/10.1016/j.enpol.2016.03.005

Köhlin, G., Parks, P. J., Barbier, E. B., & Burgess, J. C. (2001). Spatial Variability and Disincentives to Harvest: Deforestation and Fuelwood Collection in South Asia. *Land Economics*, *77*(2), 206–218. https://doi.org/10.2307/3147090

Lacey, F. G., Henze, D. K., Lee, C. J., van Donkelaar, A., & Martin, R. V. (2017). Transient climate and ambient health impacts due to national solid fuel cookstove emissions. *Proceedings of the National Academy of Sciences*, *114*(6), 1269–1274.

Lam, N. L., Upadhyay, B., Maharjan, S., Jagoe, K., Weyant, C. L., Thompson, R., … Bond, T. C. (2017). Seasonal fuel consumption, stoves, and end-uses in rural households of the far-western development region of Nepal. *Environmental Research Letters*, *12*(12), 125011. https://doi.org/10.1088/1748-9326/aa98cc

Lewis, J. J., & Pattanayak, S. K. (2012). Who Adopts Improved Fuels and Cookstoves? A Systematic Review. *Environmental Health Perspectives*, *120*(5), 637–645.

Marshall, S. J., & Biddle, S. J. (2001). The transtheoretical model of behavior change: a meta-analysis of applications to physical activity and exercise. *Annals of Behavioral Medicine*, *23*(4), 229–246.

Mensah, J. T., & Adu, G. (2015). An empirical analysis of household energy choice in Ghana. *Renewable and Sustainable Energy Reviews*, *51*, 1402–1411. https://doi.org/10.1016/j.rser.2015.07.050

Modern Ghana. (2011, May 11). Fuel wood consuming Ghana’s forest. Retrieved April 9, 2019, from Modern Ghana website: https://www.modernghana.com/news/328240/fuel-wood-consuming-ghanas-forest.html

Mudombi, S., Nyambane, A., von Maltitz, G. P., Gasparatos, A., Johnson, F. X., Chenene, M. L., & Attanassov, B. (2018). User perceptions about the adoption and use of ethanol fuel and cookstoves in Maputo, Mozambique. *Energy for Sustainable Development*, *44*, 97–108. https://doi.org/10.1016/j.esd.2018.03.004

Muller, C., & Yan, H. (2018). Household fuel use in developing countries: Review of theory and evidence. *Energy Economics*, *70*, 429–439. https://doi.org/10.1016/j.eneco.2018.01.024

NPA. (2017, October 15). Cylinder Re-circulation Module [Government]. Retrieved April 24, 2019, from Ghana National Petroleum Authority website: http://www.npa.gov.gh/news/cylinder-re-circulation-module

Owusu-Agyei, S., Ernest A. Nettey, O., Zandoh, C., Sulemana, A., Adda, R., Amenga-Etego, S., & Mbacke, C. (2012). Demographic patterns and trends in Central Ghana: baseline indicators from the Kintampo Health and Demographic Surveillance System. *Global Health Action*, *5*(1), 19033.

Piedrahita, R., Dickinson, K. L., Kanyomse, E., Coffey, E., Alirigia, R., Hagar, Y., … Hannigan, M. (2016). Assessment of cookstove stacking in Northern Ghana using surveys and stove use monitors. *Energy for Sustainable Development*, *34*, 67–76. https://doi.org/10.1016/j.esd.2016.07.007

Prochaska, J. O., & Velicer, W. F. (1997). The transtheoretical model of health behavior change. *American Journal of Health Promotion*, *12*(1), 38–48.

Puzzolo, E., Pope, D., Stanistreet, D., Rehfuess, E. A., & Bruce, N. G. (2016). Clean fuels for resource-poor settings: A systematic review of barriers and enablers to adoption and sustained use. *Environmental Research*, *146*, 218–234. https://doi.org/10.1016/j.envres.2016.01.002

Rehfuess, E. A., Puzzolo, E., Stanistreet, D., Pope, D., & Bruce, N. G. (2014). Enablers and Barriers to Large-Scale Uptake of Improved Solid Fuel Stoves: A Systematic Review. *Environmental Health Perspectives*, *122*(2), 120–130. https://doi.org/10.1289/ehp.1306639

Silge, J., & Robinson, D. (2017). *Text mining with R: A tidy approach*. O'Reilly Media, Inc.

Simon, G. L., Bailis, R., Baumgartner, J., Hyman, J., & Laurent, A. (2014). Current debates and future research needs in the clean cookstove sector. *Energy for Sustainable Development*, *20*, 49–57. https://doi.org/10.1016/j.esd.2014.02.006

Singh, D., Aung, T., & Zerriffi, H. (2018). Resource Collection Polygons: A spatial analysis of woodfuel collection patterns. *Energy for Sustainable Development*, *45*, 150–158. https://doi.org/10.1016/j.esd.2018.06.003

Smith, K. R., Bruce, N., Balakrishnan, K., Adair-Rohani, H., Balmes, J., Chafe, Z., … Rehfuess, E. (2014). Millions Dead: How Do We Know and What Does It Mean? Methods Used in the Comparative Risk Assessment of Household Air Pollution. *Annual Review of Public Health*, *35*(1), 185–206. https://doi.org/10.1146/annurev-publhealth-032013-182356

Spencer, L., Pagell, F., Hallion, M. E., & Adams, T. B. (2002). Applying the transtheoretical model to tobacco cessation and prevention: a review of literature. *American Journal of Health Promotion*, *17*(1), 7–71.

Sustainable Energy for All. (2019, April 9). Retrieved April 9, 2019, from https://www.seforall.org/sustainable-development-goal-7

Tan, C.-M., Wang, Y.-F., & Lee, C.-D. (2002). The use of bigrams to enhance text categorization. *Information Processing & Management*, *38*(4), 529–546.

Tigabu, A. (2017). Factors associated with sustained use of improved solid fuel cookstoves: A case study from Kenya. *Energy for Sustainable Development*, *41*, 81–87. https://doi.org/10.1016/j.esd.2017.08.008

Van Vliet, E. D. S., Asante, K., Jack, D. W., Kinney, P. L., Whyatt, R. M., Chillrud, S. N., … Owusu-Agyei, S. (2013). Personal exposures to fine particulate matter and black carbon in households cooking with biomass fuels in rural Ghana. *Environmental Research*, *127*, 40–48. https://doi.org/10.1016/j.envres.2013.08.009

Wang, Y., & Corson, C. (2015). The making of a ‘charismatic’ carbon credit: clean cookstoves and ‘uncooperative’ women in western Kenya. *Environment and Planning A: Economy and Space*, *47*(10), 2064–2079. https://doi.org/10.1068/a130233p

Wilson, D. L., Adam, M. I., Abbas, O., Coyle, J., Kirk, A., Rosa, J., & Gadgil, A. J. (2015). Comparing Cookstove Usage Measured with Sensors Versus Cell Phone-Based Surveys in Darfur, Sudan. In S. Hostettler, E. Hazboun, & J.-C. Bolay (Eds.), *Technologies for Development* (pp. 211–221). Springer International Publishing.

World Bank. (2014). *Clean and Improved Cooking in SubSaharan Africa*. Retrieved from http://documents.worldbank.org/curated/en/164241468178757464/pdf/98664-REVISED-WP-P146621-PUBLIC-Box393185B.pdf

CHAPTER 3

Title: Enhancing LPG Adoption in Ghana (ELAG): A factorial cluster-randomized controlled trial to enhance sustained use of clean cookstoves

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Abstract

Background: Annually, 1.6 million premature deaths are attributable to exposures from biomass combustion for cooking, known as household air pollution. Clean cookstoves curb the health effects of HAP by mitigating exposure, but health benefits are only possible when use is exclusive and sustained. The conditions under which individuals adopt and sustain use of clean cookstoves is not well understood.

Methods: We conducted a cluster-randomized controlled factorial intervention trial in Kintampo, Ghana. Rural villages (k = 27) were randomized to four intervention arms: a behavioral intervention based on the Risks, Attitudes, Norms, Abilities, and Self-Regulation (RANAS) model, an access intervention of direct LPG fuel delivery, a combined intervention of RANAS and delivery, or the control arm. 778 households participated and stove use was tracked for 12 months. We report on the final 6 months to represent sustained use rather than initial adoption. We report on imputed results due to differential missingness of outcome data in intervention arms.

Results: Imputed results yield increased use for all three intervention arms. The largest increase was for the direct delivery arm, with an increased weekly use of 4.7 minutes per week ($p<0.001$). Secondary outcomes, the number of self-reported refills, support increased use for the dual intervention arm (IRR=2.2, $p=0.026$).

Conclusion: Literature to-date demonstrates that recipients of clean cookstoves rarely achieve complete and sustained use of the new technology. Consequently, interventions are needed to influence sustained use patterns. Ensuring uptake, adoption, and sustained use of improved cookstove technologies can then lead to HAP-reductions and consequent improvements in public health. None of the interventions achieved anything close to exclusive LPG use.

Introduction

Combustion of biomass fuels in open fires is the dominant form of cooking and heating for 3 billion people worldwide. These biomass fuels include dung, wood, charcoal, and crop waste (Bonjour et al., 2013). Biomass fuels burned in inefficient cookstoves leads to high levels of particulate matter, carbon monoxide, polycyclic aromatic hydrocarbons, and other harmful air pollutants, referred to as household air pollution (HAP) (Christian, 2010; Fullerton, Bruce, & Gordon, 2008; Gustafsson et al., 2009; K. R. Smith et al., 2014; Streets et al., 2003). The health effects of HAP are significant and wide-ranging. An estimated that 1.6 million premature deaths are attributable to HAP annually (Stanaway et al., 2018). Deaths attributable to HAP occur from stroke, ischemic heart disease, pneumonia, cataracts, chronic obstructive pulmonary diseases, and lung cancer (Lim et al., 2013; K. R. Smith et al., 2014). Governments and researchers alike are working to mitigate HAP exposure. We report on one such exposure mitigation effort, a cluster-randomized cookstove sustained use study: the Enhancing LPG Adoption in Ghana (ELAG) study.

Public health proponents have looked to more efficient cookstoves to reduce HAP exposures (Mortimer et al., 2017; Kirk R. Smith et al., 2011). Several recent studies establish that clean cookstoves do not automatically reduce HAP exposures (Pope, Bruce, Dherani, Jagoe, & Rehfuess, 2017). Three factors explain this. First, simply having a new stove does not necessarily mean an individual uses it. Sustained exposure reductions are only possible when clean cookstoves are used over time. A second challenge is known as stove stacking, wherein households partially adopt the new technology while maintaining use of traditional cooking technologies (Masera, Saatkamp, & Kammen, 2000; Piedrahita et al., 2016; Ruiz-Mercado & Masera, 2015; Ruiz-Mercado, Masera, Zamora, & Smith, 2011). While partial adoption of cleaner cookstoves may reduce exposure, prior work has shown that these reductions are unlikely to reach the World Health Organization's target levels (Johnson & Chiang, 2015). Finally, cookstove interventions typically target individuals, but community-level emissions may substantially contribute to individuals' exposure (Zhou et al., 2011, 2014). While an individual household may transition to a cleaner cookstove, their neighbors may not. Therefore, large-scale adoption of clean cooking technologies may be required to decrease overall HAP exposures. These challenges motivated research to uncover the determinants of initial uptake and sustained use of new cooking technologies (Jeuland, Pattanayak, & Bluffstone, 2015; Lewis & Pattanayak, 2012; Puzzolo, Stanistreet, Pope, Bruce, & Rehfuess, 2013; Rehfuess, Puzzolo, Stanistreet, Pope, & Bruce, 2014). Ultimately, these studies seek to understand opportunities to intervene on HAP exposures.

Cookstove adoption and sustained use research spans the social, environmental, and health sciences, utilizing quantitative, qualitative, and mixed methods (Alem, Beyene, Köhlin, & Mekonnen, 2016; Bhojvaid et al., 2014; Hankey et al., 2015; Jeuland, Pattanayak, Soo, & Sheng, 2014; Stanistreet et al., 2015). The field has largely employed observational study designs to date. While these studies are informative, they may be vulnerable to selection bias since individuals opt into each group of the study by deciding whether to purchase a stove, sustain use, etc. Underlying characteristics may predict entry into each group, thus limiting the generalizability of findings. Controlled trials can address these limitations through randomization, but few studies use these designs (Beltramo, Blalock, Levine, & Simons, 2015; Bensch & Peters, 2012).

In this paper we report on the results of the ELAG study, a cluster-randomized factorial intervention trial. We provided LPG stoves to individuals in rural Ghana, thus bypassing questions of initial adoption (stove acquisition), and focus on sustained use. The objective of ELAG was to assess the effectiveness of two interventions to facilitate the sustained use of LPG. These interventions were: 1) a behavioral change intervention using the Risks, Attitudes, Norms, Abilities, and Self-Maintenance (RANAS) model, and (2) an access intervention to improve the ease of refueling LPG cylinders. The factorial design also allowed us to evaluate the interaction of these two interventions. We delivered these interventions to participants and track their stove use for one year via stove use monitors (SUMs). We define sustained use as average use in the last six months of the study, and we hypothesize that that those receiving the dual intervention will have the highest sustained use.

Methods

Study setting

The study took place in Kintampo North Municipality and Kintampo South District in the Brong-Ahafo Region of Ghana. This is a mostly rural area (population 212,198) (Ghana Statistical Service, 2019). Study households traditionally use 3-stone fires for their cooking needs. Ghana has a warm climate, with an annual average temperature between 24-30°C (Asante & Amuakwa-Mensah, 2014), so space heating is rare. There are two seasons, wet and dry/Harmattan. During the dry season most cooking takes place outdoors and enclosed or covered kitchen areas are the site of most cooking in the wet season. Wood is the main fuel source in the study area, but charcoal is used as well (Van Vliet et al., 2013).

Study Participants

ELAG participants were a subset of the Ghana Randomized Air Pollution and Health Study (GRAPHS), which was a cluster-randomized controlled trial assessing the impacts of a stove intervention on low birthweight and pneumonia (Jack et al., 2015). GRAPHS was a collaboration between the Kintampo Health Research Centre (KHRC) and Columbia University. The study had three arms, a control (3-stone fire) arm, an improved cookstove (BioLite; Brooklyn, NY), and an LPG stove. ELAG participants were limited to those enrolled in the original GRAPHS cohort and who: 1) were originally randomized to the BioLite or control arms of the study and 2) still resided in the KHRC study region (**Supplemental Figure 1**).

Ethics approval and Consent

This study received approval from the Institutional Review Board of Columbia University Medical Center and the Kintampo Heath Research Centre Institutional Ethics Committee. The study is registered with clinicaltrials.gov under NCT03352830.

Study Design

Factorial design: This study employed a factorial intervention design. There were two separate interventions, a health promotion intervention following the RANAS model, and an access intervention where some participants received direct delivery of LPG refills. We also employed a combined intervention. Each cell of the factorial design was treated as an arm of the study, resulting in four arms: 1) the Control arm, 2) the RANAS health promotion recipients, 3) the direct delivery recipients, and 4) dual intervention (RANAS and delivery) recipients. All study participants received a free first cylinder of LPG fuel with their LPG stove, but all subsequent refilling was at their own expense. This was a cluster-randomized control trial whereby randomization occurred at the village level and outcomes were measured at the household level.

Health promotion intervention: The Risks, Attitudes, Norms, Abilities, and Self-Maintenance (RANAS) model was selected to design a clean cookstove behavioral change intervention (Mosler, 2012). The RANAS model was first used in the water, sanitation, and hygiene domain. However, we recognized its potential application for clean cookstove adoption due to its emphasis of behavior change involving new technologies and its successful application in sub-Saharan Africa. The core assumption that underpins the RANAS model is that each of these five behavioral factors are necessary, but each alone is insufficient to promote behavior change. After baseline data collection, ELAG households were convened for LPG stove distribution and (if relevant) the behavioral change intervention. A research team member from KHRC and a peer-adopter collaborated to deliver the intervention. The peer-adopter was a participant from a GRAPHS LPG community who has sustained use of LPG after study conclusion.

A series of activities were undertaken to address each RANAS behavioral factor (**Table 1**). Details of the intervention have been published previously (Carrión et al., 2018). First, we explained the health risks associated with exposure to HAP. For attitudinal factors, we discussed perceptions of time, money, and effort associated with the behavior change, and the benefits of the new behavior. Normative factors were addressed via establishment of group-level and individual-level expectations, i.e. the group delivery of the intervention, in the presence of peers and community leaders. The LPG peer adopter was also asked to provide a testimonial regarding their experiences using LPG and overall appreciation of the technology. Ability-related behavioral factors entailed a food demonstration by the peer-adopter where they cooked a typical meal on the LPG stove. We also provided a financial literacy orientation so that participants would consider saving for future LPG purchases. Self-regulation factors refer to continued orientation to the desired behavior given that personal and broader circumstances are oriented towards traditional cookstove use. ELAG addressed this factor by contracting and training Community-based Surveillance Volunteers (CBSVs) who visited participants weekly to discuss the potential barriers to sustained use and brainstorm possible solutions. The CBSVs are community liaisons for the longstanding Kintampo Demographic and Health Surveillance system (Owusu-Agyei et al., 2012).

Table 1: Overview of RANAS intervention.

Risks: Education on the health impacts of HAP exposure, and potential benefits of mitigation.
Attitudes: Discussion of non-health benefits of clean cooking, including time savings, safety, and cleaner pots/utensils.
Norms: Convening intervention with other participants in a public setting, prompting collective commitment to using LPG, discussing government policies towards clean cooking.
Abilities: Financial orientation – strategies to save for LPG refills. Identifying all refill locations. Having a peer LPG adopter: do a cooking demonstration, discuss a time when they could not refill due to financial or logistical constraints.
Self-Regulation: Weekly follow-up visits from a community member contracted by the study.

Access intervention: Energy access research underscores the importance of the 'last mile' (or, more realistically in rural Ghana, last 30 km) of LPG delivery/accessibility (Carrión, et al., 2019). Few studies have tested how much these logistical barriers impact user demand (WLPGA, 2015). To directly test the extent to which transportation costs limit LPG use, the ELAG access intervention employed community-based taxi drivers to refill LPG cylinders for participants. We contracted and paid the drivers for the delivery services, but participants were responsible for the cost of the refill.

Randomization: We used a covariate-constrained randomization approach with prognostic covariates to assign clusters to study arms (Ivers et al., 2012; Moulton, 2004). We chose this approach because of its efficiency in dealing with imbalance, which can reduce statistical power in a cluster design. **Table 2** presents the balance variables and their rationale. Allocation amongst arms was randomly designated when imbalance was below the maximum threshold. An independent epidemiologist performed the final randomization using the *ccrand* procedure in Stata. Allocation was not revealed to field staff until after baseline data collection was completed.

Table 2: Variables chosen for covariate constrained randomization

Variable	Rationale
Community Asset Index	Studies have shown that differential access to resources can be predictive in the uptake of new cookstove technologies (Lewis & Pattanayak, 2012; Rehfuess et al., 2014).
Average Household Size	Studies have shown that household size can be predictive in the uptake of new cookstove technologies (Lewis & Pattanayak, 2012; Rehfuess et al., 2014).
Distance to Refueling Station	Participant villages are scattered throughout the region at varying distances from the refueling center. Further distances are likely a deterrent to refuel for non-Agent delivery households*,* **Supplemental Figure 1**.
Households per cluster	To ensure roughly equal number of participating households per arm.

Data collection and management

Baseline data: Baseline demographic and socioeconomic status surveys were administered. We constructed an asset index using a principal components analysis of variables including type of housing materials, type of toilet facility, primary water source, type of home ownership, household ownership of livestock animals, and household ownership of consumer durables (Gunnsteinsson et al., 2010). A pre/post-test of the RANAS model behavioral factors was administered in order to assess changes in participants' knowledge, perceptions, or attitudes regarding HAP and/or LPG stoves. We also assessed the potential role of gender dynamics on sustained use. An intrahousehold relationship score was tabulated from a validated questionnaire probing relationship quality (Ruark et al., 2017). The questionnaire entails direct questions about financial decisions in the home, along with other relationship dynamics. Field staff administered surveys, which were later reviewed by field supervisors for completeness and consistency.

Stove use monitoring: The principal outcome was average weekly cooking time (minutes per week) using an LPG stove during the last 6 months of the study. This time period was of interest in order to assess the effectiveness of the intervention on sustained use rather than initial adoption. Stove use was measured via stove use monitors (SUMs). Each stove was equipped with Maxim iButton temperature loggers programmed to collect temperature data at ten minute intervals (Ruiz-Mercado, Canuz, & Smith, 2012). This left the memory at capacity after two weeks. Field staff visited households every two weeks to download the data. Monitors were used to determine minutes of stove use during that period. Raw temperature data was transformed into a 'duration of cooking events' variable using the *AnomalyDetection* package in R (Twitter, 2014/2019). This package was originally developed to detect anomalies in internet traffic. However, when applied to temperature data, the algorithm detects events that deviate from the ambient diurnal temperature pattern. We applied numerous filters to the processing and only considered positive slope anomalies and those above 35˚C as cooking time. Field staff visited households every two weeks to download SUMS data.

Other measures of use: Field staff assessed two other measures of use during biweekly visits. First, fieldworkers weighed LPG cylinders with an EatSmart Precision Voyager Digital Luggage scale. Second, they also administered an LPG stove use questionnaire, including whether or not the household had refilled their cylinders since the last visit.

Data Analyses

Primary Analysis: We examine the effect of the intervention on average stove use over the final six months of the observation by comparing the three intervention arms to the control. Arithmetic means are calculated and p values are derived from a log-linear linear panel regression with fixed effects for study participant and week of measurement.

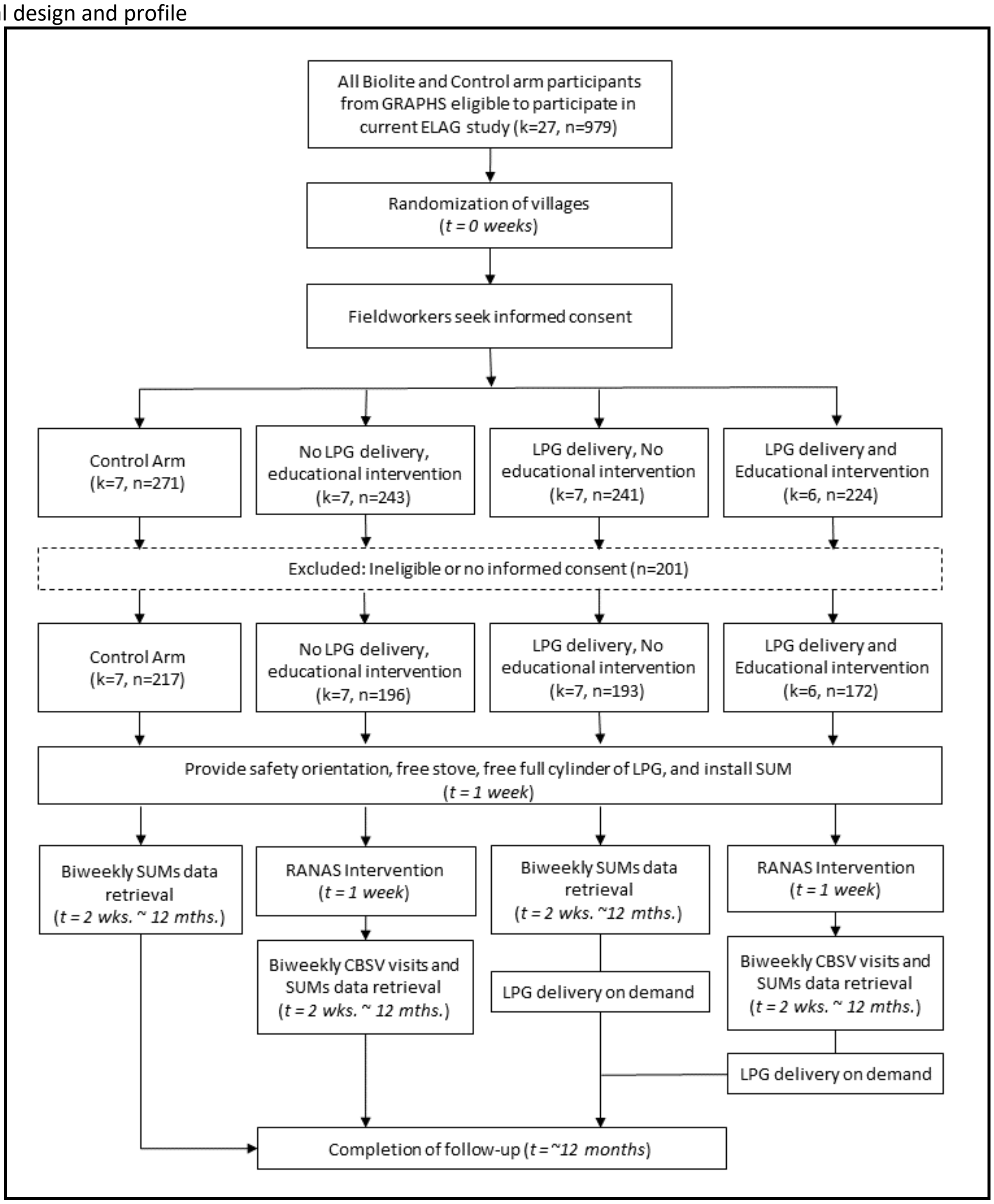
Missing stove use data: Gathering complete stove use time series proved to be challenging. Major issues included SUMs failure (due to high temperature or moisture exposure) and missed data download visits. While we obtained some data on all participants, the amount of missingness was differential by study arm, with greater missingness in the direct delivery and dual intervention arms of the study (**Supplemental Figure 2** and **Supplemental Table 1**). To address this limitation, we leveraged the biweekly cylinder-weighing data to create a predictive model of weekly stove use using the times we had data overlap. Differences in biweekly weights were calculated and linearly interpolated to provide a weekly estimate. That estimate was combined with other variables, specifically: arm of study, household size, participant's education, ethnicity, season, and asset index. We tested several regression types, and found that an ordinary least squares model minimized the root mean squared error and the mean absolute error in a 10-fold 10-repeat cross validation. We repeated the primary analyses with observed values and the predicted estimates when the observed values were missing.

Secondary outcomes: We also reported on the number of self-reported refills by arm of the study as a function of observation time. Unadjusted incidence rate ratios were computed with the number of refills and the number of fieldworker visits for all participant households in a given arm.

Heterogeneity of treatment effect: Subgroups may respond differently to the intervention based on socio-demographic characteristics. We used regression analysis to assess differences in subgroup effect by modeling potential interactions between study arm and sociodemographic variables of interest. The outcome was summed minutes of LPG use in the last 6 months of the study. This variable was right-skewed, so we perform a log-linear regression with cluster-robust standard errors by village to account for potential clustering of observations.

Results

Figure 1: Trial design and profile



Trial profile and participant characteristics

There were 979 eligible households in our study (**Figure 1**). We cluster-randomized all villages before enrollment, yielding seven villages in the Control arm (n = 271), seven in the direct delivery arm (n = 243), seven in the RANAS education arm (n = 241), and six in the dual intervention (n =224). Overall, 201 were either ineligible due to leaving the study area, or chose not to participate. The remaining sample size was 778. There was no attrition after enrollment. However, there was significant data loss, differential by study arm (**Supplemental Table 1**).

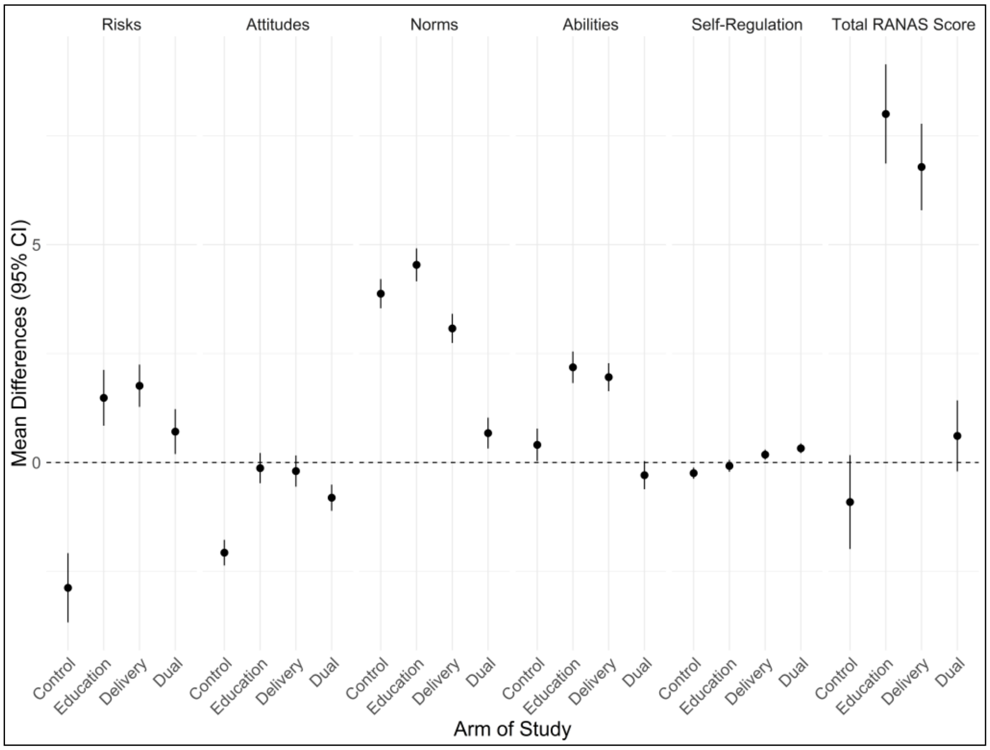
Table 3: Baseline characteristics by study arm.

	Control (N=217)	Education (N=196)	Delivery (N=193)	Dual (N=172)	Total (N=778)
Participant's Age					
Mean (SD)	31.1 (7.1)	31.8 (7.7)	31.0 (7.1)	32.0 (7.4)	31.4 (7.3)
Ethnicity					
Akan	78 (35.9%)	17 (8.7%)	41 (21.2%)	41 (23.8%)	177 (22.8%)
Grushi	8 (3.7%)	25 (12.8%)	22 (11.4%)	6 (3.5%)	61 (7.8%)
Dagarti	54 (24.9%)	74 (37.8%)	47 (24.4%)	37 (21.5%)	212 (27.2%)
Mo	6 (2.8%)	53 (27.0%)	41 (21.2%)	16 (9.3%)	116 (14.9%)
Konkomba	44 (20.3%)	9 (4.6%)	18 (9.3%)	29 (16.9%)	100 (12.9%)
Other	27 (12.4%)	18 (9.2%)	24 (12.4%)	43 (25.0%)	112 (14.4%)
Religion					
Christian	153 (70.5%)	143 (73.0%)	137 (71.0%)	118 (68.6%)	551 (70.8%)
Non-Christian	64 (29.5%)	53 (27.0%)	56 (29.0%)	54 (31.4%)	227 (29.2%)
Household size					
2-5 persons	75 (34.6%)	53 (27.0%)	74 (38.3%)	68 (39.5%)	270 (34.7%)
6-10 persons	116 (53.5%)	112 (57.1%)	98 (50.8%)	89 (51.7%)	415 (53.3%)
More than 10 persons	26 (12.0%)	31 (15.8%)	21 (10.9%)	15 (8.7%)	93 (12.0%)
Profession					
Professional	2 (1.0%)	2 (1.3%)	0 (0.0%)	1 (0.7%)	5 (0.8%)
Secretarial	0 (0.0%)	0 (0.0%)	0 (0.0%)	0 (0.0%)	0 (0.0%)
Trader	68 (35.6%)	56 (36.1%)	65 (40.9%)	44 (29.5%)	233 (35.6%)
Seamstress	7 (3.7%)	12 (7.7%)	16 (10.1%)	8 (5.4%)	43 (6.6%)
Farmer	114 (59.7%)	85 (54.8%)	78 (49.1%)	94 (63.1%)	371 (56.7%)
Other	0 (0.0%)	0 (0.0%)	0 (0.0%)	2 (1.3%)	2 (0.3%)
Participant's Education (years)					
Mean (SD)	6.5 (5.7)	6.4 (5.8)	7.6 (5.6)	6.3 (5.7)	6.7 (5.7)
Wealth Index quintile					
1 (very poor)	49 (22.6%)	43 (21.9%)	35 (18.1%)	27 (15.7%)	154 (19.8%)
2	49 (22.6%)	43 (21.9%)	31 (16.1%)	34 (19.8%)	157 (20.2%)
3	43 (19.8%)	37 (18.9%)	41 (21.2%)	37 (21.5%)	158 (20.3%)
4	40 (18.4%)	37 (18.9%)	40 (20.7%)	38 (22.1%)	155 (19.9%)
5 (least poor)	36 (16.6%)	36 (18.4%)	46 (23.8%)	36 (20.9%)	154 (19.8%)

Table 3 outlines baseline participant characteristics. Participants are roughly equal in most respects. On average, participating women are slightly above 30 years old, mostly Christian, live in households of 6-10 people, and have approximately 6 years of formal education.

Effect of intervention RANAS factors

Figure 2: Mean differences in RANAS pre and post-tests by arm of ELAG. Scoring is positive when oriented toward behavior change, and the test is out of 105 points. 95% confidence intervals from paired t-tests, n = 778.



We administered an evaluation on the five RANAS behavioral factors at baseline and at study closeout. The maximum score on the evaluation was 105 points. Overall scores had a mean of 86.7 points at baseline and 90.3 at study closeout. We present mean differences by arm (**Figure 2**). The total RANAS score did not change significantly for the control arm (-0.91 points, 95% CI: -1.99-0.17) or the dual intervention arm (0.61 points, 95% CI: -0.2-1.42). However, the total RANAS score did increase for the RANAS education arm by 8 points (95% CI: 6.86-9.14), which represents a 9.3% increase from the baseline score. The direct delivery arms increased by 6.78 points (95% CI: 5.79-7.78), which is a 7.8% increase from the baseline score. The Control and RANAS education arms moved in the expected directions, but the direct delivery and dual intervention did not. The most notable differences within the specific RANAS factors include a decrease in the risks score for the Control arm while all other arms exhibited small increases. Attitudes either did not change (RANAS education and direct delivery) or decreased (control and dual intervention). Norms increased for all groups, but the least for the dual intervention (0.67 points, 95% CI: 0.32-1.03) and abilities increased for all groups except the dual intervention (-0.29 points, 95% CI: -0.61-0.03). Intervention tracking data showed a lower number of CBSV visits in the dual intervention arm rather than the RANAS education arm. There were an average of 3 visits per participant in the dual intervention arm (634 total visits) and 8 visits per participant in the RANAS education arm (1846 total visits).

Effect of Intervention on Sustained Use

Table 4 outlines the main results of the study. We found that the RANAS education arm of the study achieved the highest sustained use in the last 6 months of ELAG, compared to the control arm ($p=0.0014$). The magnitude of this difference was small, 0.14 minutes (~9 seconds) per week. The direct delivery and dual intervention arms showed decreased use compared to the control arm (Delivery: $p<0.0001$, Dual: $p=0.0496$). We found, however, that there was differential missingness by arm (**Supplemental Figure 2**). Those with higher levels of missingness were younger participants in smaller households, which we believe resulted in a downward bias (**Supplemental Table 2**). Therefore, we created an imputation model to account for missing observations.

Table 4: Comparison of weekly stove use (in minutes) by arm of study in the last six months of the observation period. P values produced from linear model with respondent fixed effects. Values in bold have a p value less than 0.05, N = 778.

	Arm	Mean	P value
Results without imputation	Control	17.48	*Reference*
	Education	**17.62**	0.0014
	Delivery	**13.42**	<0.001
	Dual	**13.08**	0.0496
Results with Imputation	Control	22.48	*Reference*
	Education	**25.18**	<0.001
	Delivery	**27.17**	<0.001
	Dual	**23.46**	<0.001

Our imputed results show that all intervention arms had a statistically significant increase in sustained use. The dual intervention arm had the smallest increase (23.46 minutes per week, p<0.0001) and the direct delivery arm had the largest (27.17 minutes per week, p<0.0001). This represents an average increase of 4.7 minutes per week compared to the control arm. Over the sustained use period, this difference equated to 122 additional minutes of use.

Alternate measures of sustained use

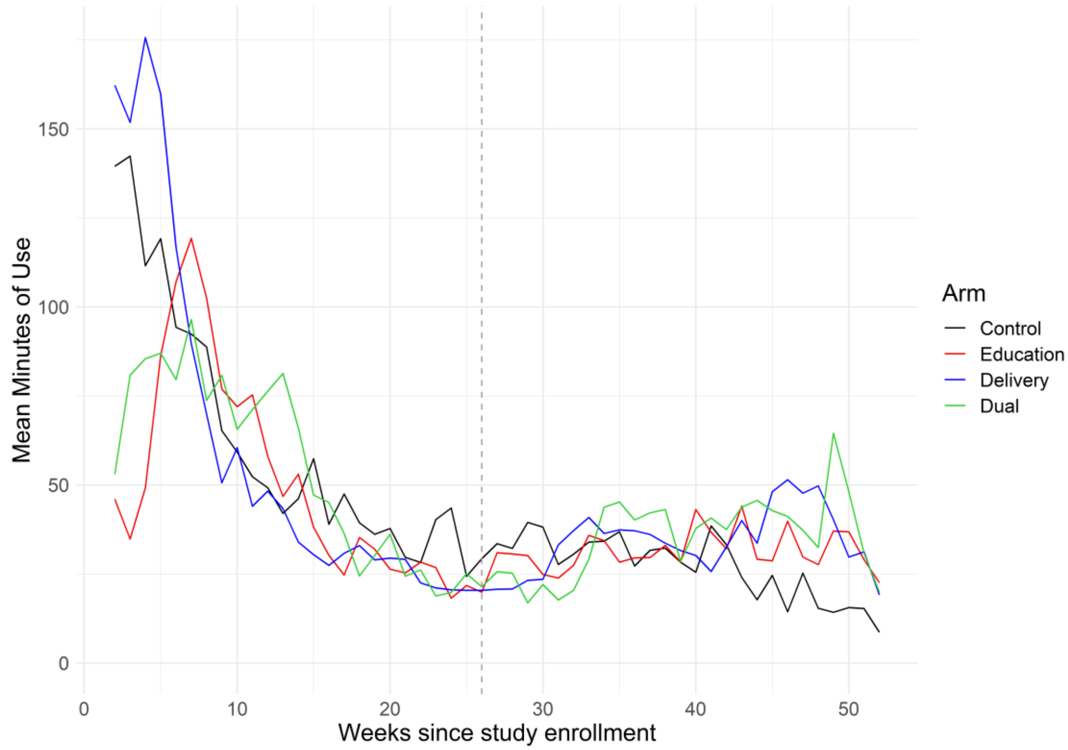
We assessed the consistency of our results by examining alternate measures of sustained use (**Table 5**). Fieldworkers administered biweekly questionnaires over the course of the study. One question asked whether participants had refilled their cylinder since the last visit. We used the self-reported number of refills as an alternate event of interest. We found that the dual intervention arm a higher incidence of refills per weeks of visits (IRR: 2.2, p = 0.026) when compared to the control arm. No other arms demonstrated significant differences.

Table 5: Results from secondary measure of use: self-reported refills during bi-weekly fieldworker visits. Analysis for the last 6 months of the study period and full year of follow up. Incidence rate calculated with total refills and surveillance time (household visit weeks). P value calculated with Fisher's test. Statistically significant values in bold. Households = number of unique households that refilled their cylinders.

	Biweekly Visits (last 6 months)					**Biweekly Visits (full year)**				
Arm	**Refills**	**House-holds**	**Visit Weeks**	**Incidence Rate Ratio**	**P value**	**Refills**	**House-holds**	**Visit Weeks**	**Incidence Rate Ratio**	**P value**
Control	17	14	1705	*Reference*		29	23	3428	*Reference*	
Education	27	26	1676	1.62	0.131	55	44	3236	**2.01**	**0.002**
Delivery	12	12	1045	1.15	0.705	33	27	2269	**1.71**	**0.037**
Dual	15	12	683	**2.2**	**0.026**	27	23	1338	**2.38**	**0.002**

The refills were tracked over the entire study period, so we also examine differences in refills over the full year of follow up. We find that all three intervention arms have a higher number of refills over the entire study period compared to the control arm. The highest incidence of refills again took place in the dual intervention arm, with an incidence rate ratio of 2.38 (p=0.002) when compared to the control arm. A higher incidence of refills emerges for the RANAS education arm (IRR: 2.01, p = 0.002) and the direct delivery arm (IRR: 1.71, p=0.037).

Figure 3: Time series of use over the entire study period, relative to date of enrollment, including imputed values. Dashed line = 6 months.



We visualized use over the study period to understand potential temporal trends relative to study enrollment (**Figure 3**) and based on calendar time (**Supplemental Figure 3**). Relative to study enrollment, participants in all four arms show higher use during the first six months when compared to the last six months. The control arm follows a downward trend around week 40 onward. All three intervention arms appear to reach just before study closeout, and then decreased until the end of the study. All study arms ended follow up with a downward trajectory of weekly minutes of use.

Heterogeneity of treatment effect

We assess potential heterogeneity of treatment effect by participant socio-demographic characteristics (**Supplemental Table 3**). In addition to ethnicity, age, education, and other standard characteristics, we also test for differences based on a relationship score. We were interested to assess potential differences in impact of the interventions based on intrahousehold asymmetries in resource control. Our analysis demonstrated no evidence of differences of sustained use by study arm and socio-demographic variables when comparing to the control arm. It is possible we did not have sufficient statistical power for subgroup analysis given that a higher sample size is typically required to detect effect measure modification rather than a main effect.

Discussion

ELAG was a cluster-randomized controlled intervention trial to estimate the differences in sustained use of clean cookstoves caused by two separate interventions, and a combined intervention. We found that the RANAS educational intervention led to increases in knowledge and attitudes towards behavior change. However, we also observed unexpected increases in the direct delivery arm and no change in the dual intervention arm. We hypothesized that the dual intervention arm would demonstrate the highest levels of sustained use. While we were limited by data loss, our results suggest that these interventions may yield increases in sustained use of clean cookstoves over time. Results were the most consistent for the RANAS educational intervention arm, which demonstrated increased use in our primary results with and without imputation, and the incidence of refills over the 12-month follow up. This was also the only intervention arm that did not experience substantial data loss. Results from the direct delivery and dual intervention arms are inconsistent, but suggestive of increased sustained use. All differences are, however, small in magnitude. We found no evidence of heterogeneities in treatment effect. Unpublished stove use monitoring data from exclusive 3-stone fire stove users in 2015 demonstrates an average weekly cooking time of 1,260 minutes per week, and an interquartile range of 560-1,680 minutes. Results from ELAG show an average of 4.7 minutes of increased LPG use for the direct delivery arm. This low overall LPG, relative to background 3-stone fire use, indicates extensive stove stacking and underscores the challenges in achieving clean cooking objectives in rural Ghana.

Our study did yield unexpected results. We found that individuals with the dual intervention had no change in their knowledge and attitudes based on the RANAS pre and post-test comparison. This is unexpected given that the RANAS education arm demonstrated positive and statistically significant changes. It is possible that a lower number of follow-up visits by CBSVs in the dual intervention arm explains some of this difference. We recommend future studies on the effectiveness of the RANAS model with particular focus on contextual factors of intervention delivery, including fidelity to intervention design and potential differences in receptivity based on demographic factors. It is worth noting that participants had high overall baseline scores on the RANAS behavioral factors, implying high background knowledge of the benefits of LPG and positive attitudes towards behavior change.

Another unexpected result was the observed decreases in use for the direct delivery and dual intervention arms. We believe these results arose due to downward bias of differentially missing observations in those two arms. We attempted to account for this with an imputation model, which demonstrated associations in line with our a priori hypotheses. The imputation model showed a modest increase in sustained use in the dual intervention arm, and our secondary measures identified a higher number of refills. Beyond data loss, a notable limitation of our study is the lack of stove use monitoring for traditional fuels. Our goal is to reduce and ultimately displace traditional fuel use. Without these measurements, we are unable to establish the effectiveness of our interventions on decreasing traditional stove use. Finally, our intervention does not control for the potential role of fuel price, which could have substantial influence on use. Ongoing research in northern Ghana demonstrates a high willingness to pay for clean or improved cookstoves, above market rates, but a willingness to pay for LPG fuel that is substantially below market rates (Dickinson, 2019).

This study has many strengths. We chose two scalable interventions that are particularly germane in our study region. For many years, the Ghanaian government has been trying to increase LPG uptake in rural areas (Asante et al., 2018). To this end, the government established a distribution program of free

LPG stoves and empty cylinders in rural areas. Our work has shown that recipients of those stoves have low levels of sustained use (Abdulai et al., 2018). Therefore, a RANAS intervention can be included in the distribution process of stoves to increase use. Additionally, the Ghanaian government is currently overhauling the distribution system for LPG fuel nationwide (NPA, 2017). Our direct delivery service could inform the potential benefits of increased LPG accessibility in rural areas. This study also benefits from a randomized design to overcome selection biases and test the effects of interventions. In fact, to our knowledge, this was the first randomized study of clean cookstove sustained use. We used several measures of stove use to triangulate use patterns, and a considerable follow up time, which should overcome social desirability biases (Wilson et al., 2015).

Conclusion

This study contributes to the literature on sustained use of clean cookstoves by employing novel interventions and a randomized design. We show that the RANAS health behavior model and a direct delivery intervention may offer marginal gains in sustained use of clean cookstoves. Unfortunately, the interventions had small impacts that indicate persistent stove stacking. Future studies should consider the role of price in sustained use and displacing traditional fuels. Only by decreasing traditional fuel use can we appreciate the health benefits of clean cooking.

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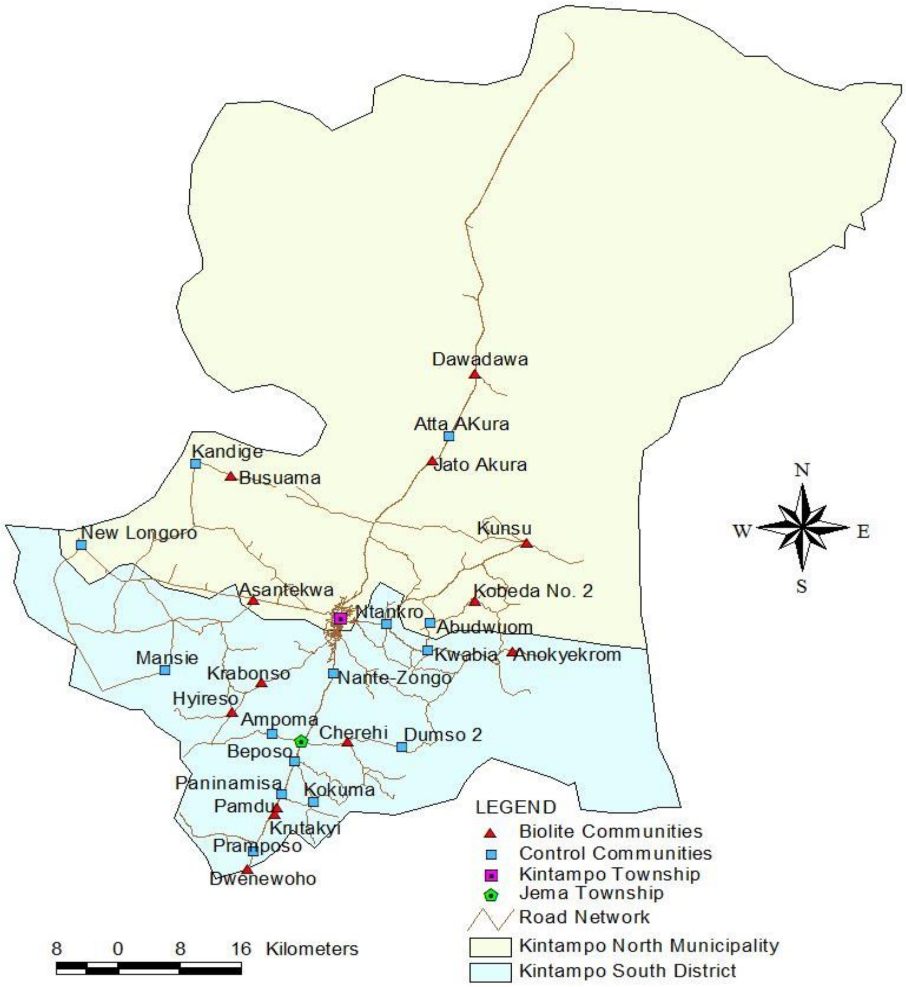
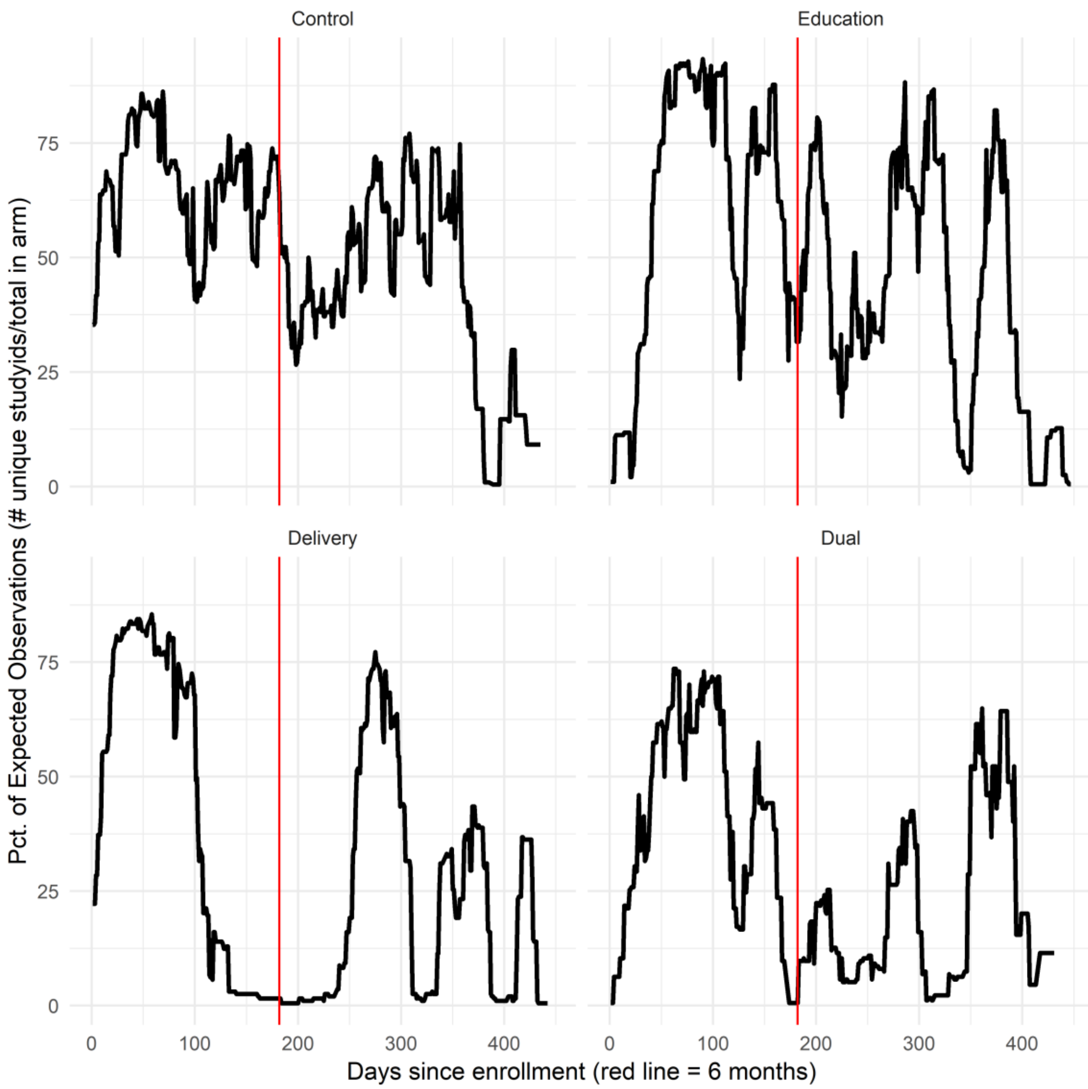
Supplemental Materials

Supplemental Figure 1: Map of the study region.



Supplemental Figure 2: Percent of expected daily observations by arm of study.



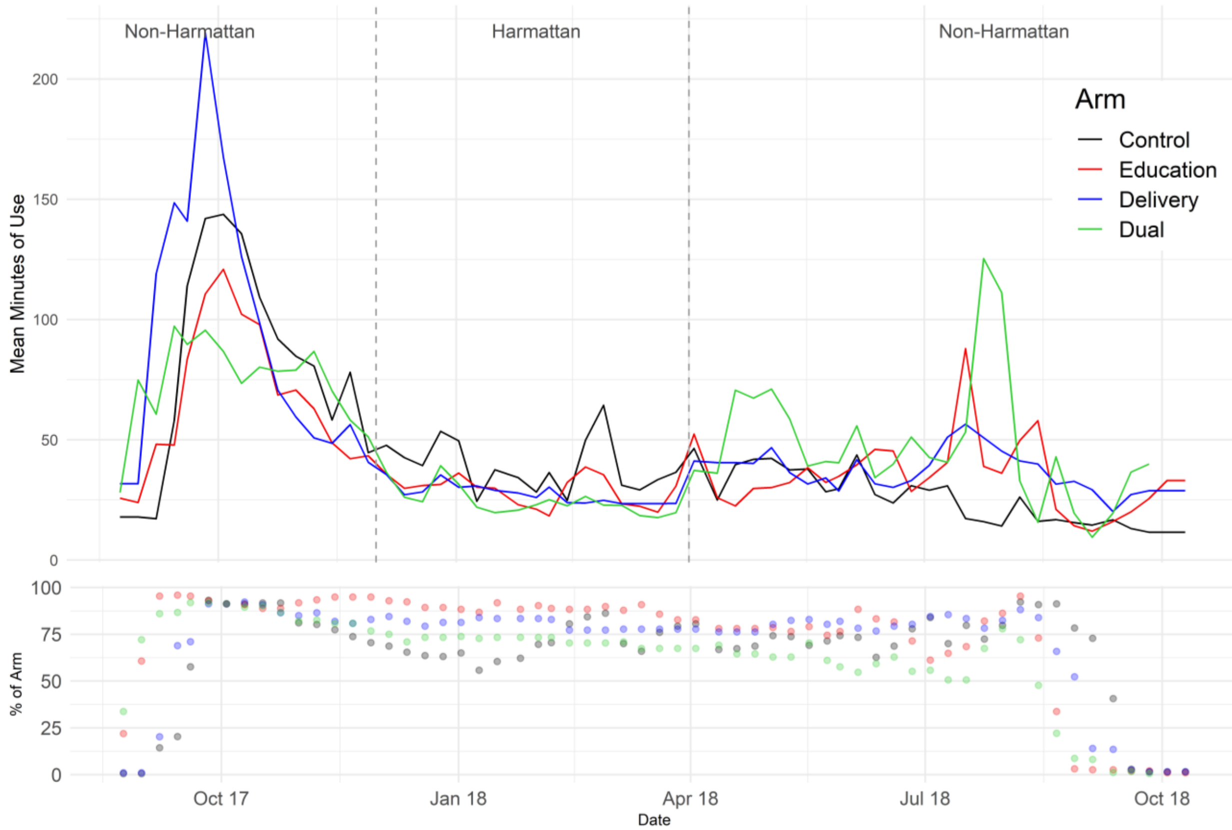
Supplemental Table 1: Missingness by arm. Participants for whom there are at least 30 days' worth of stove use monitoring data.

	Control	**RANAS Education**	**Direct Delivery**	**Dual**
Participants with 30+ days of observations	201	184	155	140
Total enrolled	217	196	193	172
Percent for main analysis	92.6%	93.9%	80.3%	81.4%

Supplemental Table 2: Characteristics of those who have less than one month's worth of data in the latter six month period.

	Missing (N=98)	Not Missing (N=680)	Total (N=778)	p value
Participant's Age				0.049
Mean (SD)	30.1 (7.2)	31.6 (7.3)	31.4 (7.3)	
Ethnicity				0.312
Akan	27 (27.6%)	150 (22.1%)	177 (22.8%)	
Other	15 (15.3%)	97 (14.3%)	112 (14.4%)	
Grushi	10 (10.2%)	51 (7.5%)	61 (7.8%)	
Dagarti	28 (28.6%)	184 (27.1%)	212 (27.2%)	
Mo	11 (11.2%)	105 (15.4%)	116 (14.9%)	
Konkomba	7 (7.1%)	93 (13.7%)	100 (12.9%)	
Religion				0.705
Christian	71 (72.4%)	480 (70.6%)	551 (70.8%)	
Non-Christian	27 (27.6%)	200 (29.4%)	227 (29.2%)	
Household size				< 0.001
2-5 persons	53 (54.1%)	217 (31.9%)	270 (34.7%)	
6-10 persons	41 (41.8%)	374 (55.0%)	415 (53.3%)	
More than 10 persons	4 (4.1%)	89 (13.1%)	93 (12.0%)	
Profession				0.352
Professional	0 (0.0%)	5 (0.9%)	5 (0.8%)	
Secretarial	0 (0.0%)	0 (0.0%)	0 (0.0%)	
Trader	26 (32.1%)	207 (36.1%)	233 (35.6%)	
Seamstress	4 (4.9%)	39 (6.8%)	43 (6.6%)	
Farmer	50 (61.7%)	321 (56.0%)	371 (56.7%)	
Other	1 (1.2%)	1 (0.2%)	2 (0.3%)	
Participant's Education (years)				0.009
Mean (SD)	8.1 (5.4)	6.5 (5.7)	6.7 (5.7)	
Wealth Index quintile				0.744
1 (very poor)	21 (21.4%)	133 (19.6%)	154 (19.8%)	
2	17 (17.3%)	140 (20.6%)	157 (20.2%)	
3	17 (17.3%)	141 (20.7%)	158 (20.3%)	
4	23 (23.5%)	132 (19.4%)	155 (19.9%)	
5 (least poor)	20 (20.4%)	134 (19.7%)	154 (19.8%)	

Supplemental Figure 3: Time series of use of observed and imputed stove use. Top panel = mean minutes of use in a given calendar week; Bottom panel = proportion of study arm with data on a given week.



Supplemental Table 2: Sub group analysis of treatment effect via log linear regression with interactions between socio-demographic variable (term) and treatment arm on cooking time in the final 6 months of ELAG. Values = point estimate (95% confidence intervals).

Term	Delivery	Dual	Education
Participant's Age	-0.01 (-0.03-0.01)	-0.02 (-0.04-0.01)	0 (-0.02-0.03)
Asset index	-0.06 (-0.14-0.03)	0.04 (-0.04-0.13)	-0.04 (-0.12-0.04)
Ethnicity (reference = Akan)			
Dagarti	-0.01 (-0.63-0.61)	0.53 (-0.21-1.27)	-0.14 (-0.91-0.63)
Grushi	0.57 (-0.28-1.42)	0.34 (-0.78-1.45)	-0.22 (-1.17-0.74)
Konkomba	-0.36 (-1.16-0.45)	0.05 (-0.76-0.87)	-1 (-1.89--0.11)
Mo	-0.17 (-1.17-0.84)	-0.17 (-1.33-0.98)	-0.39 (-1.53-0.74)
Other	0.23 (-0.54-1.01)	0.28 (-0.47-1.03)	-0.17 (-1.03-0.7)
Household Size (reference = 2-5 people)			
HHSize6-10 people	0.25 (-0.13-0.62)	0.16 (-0.23-0.55)	0.25 (-0.14-0.65)
HHSize>10 people	0.26 (-0.33-0.86)	0.54 (-0.11-1.19)	0.36 (-0.22-0.95)
Relationship Score	0 (-0.04-0.03)	0 (-0.04-0.03)	0.01 (-0.03-0.04)
Religion (reference = Christian)			
Non-Christian	0.13 (-0.27-0.52)	-0.15 (-0.61-0.31)	-0.04 (-0.45-0.37)
Profession (reference = Professional)			
Farmer/Domestic Worker	-0.09 (-0.63-0.44)	-1 (-3.12-1.13)	-0.79 (-2.54-0.96)
Secretarial	-0.14 (-0.69-0.41)	-1.44 (-3.57-0.69)	-0.58 (-2.34-1.18)
Trader	0.69 (-0.21-1.6)	-1.12 (-3.43-1.19)	0.1 (-1.82-2.01)
Unknown/No Response	NA	-0.68 (-2.86-1.5)	-0.74 (-2.53-1.04)

References

Abdulai, M. A., Afari-Asiedu, S., Carrion, D., Ae-Ngibise, K. A., Gyaase, S., Mohammed, M., … Jack, D. (2018). Experiences with the Mass Distribution of LPG Stoves in Rural Communities of Ghana. *EcoHealth*, *15*(4), 757–767. https://doi.org/10.1007/s10393-018-1369-7

Alem, Y., Beyene, A. D., Köhlin, G., & Mekonnen, A. (2016). Modeling household cooking fuel choice: A panel multinomial logit approach. *Energy Economics*, *59*, 129–137.

Anomaly Detection with R. Contribute to twitter/AnomalyDetection development by creating an account on GitHub. (2019, May 13). Retrieved May 13, 2019, from https://github.com/twitter/AnomalyDetection (Original work published December 9, 2014)

Asante, F., & Amuakwa-Mensah, F. (2014). Climate Change and Variability in Ghana: Stocktaking. *Climate*, *3*(1), 78–99. https://doi.org/10.3390/cli3010078

Asante, K. P., Afari-Asiedu, S., Abdulai, M. A., Dalaba, M. A., Carrión, D., Dickinson, K. L., … Jack, D. W. (2018). Ghana's rural liquefied petroleum gas program scale up: A case study. *Energy for Sustainable Development*, *46*, 94–102. https://doi.org/10.1016/j.esd.2018.06.010

Beltramo, T., Blalock, G., Levine, D. I., & Simons, A. M. (2015). Does Peer Use Influence Adoption of Efficient Cookstoves? Evidence From a Randomized Controlled Trial in Uganda. *Journal of Health Communication*, *20*(sup1), 55–66. https://doi.org/10.1080/10810730.2014.994244

Bensch, G., & Peters, J. (2012). *A Recipe for Success? Randomized Free Distribution of Improved Cooking Stoves in Senegal* (SSRN Scholarly Paper No. ID 2030746). Retrieved from Social Science Research Network website: http://papers.ssrn.com/abstract=2030746

Bhojvaid, V., Jeuland, M., Kar, A., Lewis, J. J., Pattanayak, S. K., Ramanathan, N., … Rehman, I. H. (2014). How do People in Rural India Perceive Improved Stoves and Clean Fuel? Evidence from Uttar Pradesh and Uttarakhand. *International Journal of Environmental Research and Public Health*, *11*(2), 1341–1358. https://doi.org/10.3390/ijerph110201341

Bonjour, S., Adair-Rohani, H., Wolf, J., Bruce, N. G., Mehta, S., Prüss-Ustün, A., … Smith, K. R. (2013). Solid Fuel Use for Household Cooking: Country and Regional Estimates for 1980–2010. *Environmental Health Perspectives*, *121*(7), 784–790. https://doi.org/10.1289/ehp.1205987

Carrión, D., Dwommoh, R., Tawiah, T., Agyei, O., Agbokey, F., Twumasi, M., … Asante, K. P. (2018). Enhancing LPG adoption in Ghana (ELAG): a factorial cluster-randomized controlled trial to Enhance LPG Adoption & Sustained use. *BMC Public Health*, *18*(1), 689. https://doi.org/10.1186/s12889-018-5622-3

Carrión, Daniel, Prah, Rebecca, Gould, Carlos, Mujtaba, Mohammed, Agyei, Oscar, Tawiah, Theresa, … Asante, Kwaku Poku. (2019). *Using longitudinal survey and sensor data to understand the social and ecological determinants of suspended clean cookstove use in rural Ghana*.

Christian, T. J. (2010). Trace gas and particle emissions from domestic and industrial biofuel use and garbage burning in central Mexico. *Atmospheric Chemistry and Physics*, *10*(2), 565–584. https://doi.org/10.5194/acp-10-565-2010

Dickinson, K. (2019, May). *Economic experiments to measure LPG stove demand and impacts on cooking behaviors and exposures in Northern Ghana*. Oral Presentation presented at the Sustainable Energy Transitions Initiative annual meeting, Santiago, Chile.

Fullerton, D. G., Bruce, N., & Gordon, S. B. (2008). Indoor air pollution from biomass fuel smoke is a major health concern in the developing world. *Transactions of the Royal Society of Tropical Medicine and Hygiene*, *102*, 843–851.

Ghana Statistical Service. (2019). *Projected population by region and sex, 2010, 2015-2020*. Retrieved from http://statsghana.gov.gh/nationalaccount_macros.php?Stats=MTA1NTY1NjgxLjUwNg==/webstats/s679n2sn87

Gunnsteinsson, S., Labrique, A. B., West, K. P., Christian, P., Mehra, S., Shamim, A. A., … Klemm, R. D. (2010). Constructing Indices of Rural Living Standards in Northwestern Bangladesh. *Journal of Health, Population and Nutrition*, *28*(5). https://doi.org/10.3329/jhpn.v28i5.6160

Gustafsson, Ö., Kruså, M., Zencak, Z., Sheesley, R. J., Granat, L., Engström, E., … Rodhe, H. (2009). Brown Clouds over South Asia: Biomass or Fossil Fuel Combustion? *Science*, *323*(5913), 495. https://doi.org/10.1126/science.1164857

Hankey, S., Sullivan, K., Kinnick, A., Koskey, A., Grande, K., Davidson, J. H., & Marshall, J. D. (2015). Using objective measures of stove use and indoor air quality to evaluate a cookstove intervention in rural Uganda. *Energy for Sustainable Development*, *25*, 67–74. https://doi.org/10.1016/j.esd.2014.12.007

Ivers, N. M., Halperin, I. J., Barnsley, J., Grimshaw, J. M., Shah, B. R., Tu, K., … Zwarenstein, M. (2012). Allocation techniques for balance at baseline in cluster randomized trials: a methodological review. *Trials*, *13*, 120.

Jack, D. W., Asante, K. P., Wylie, B. J., Chillrud, S. N., Whyatt, R. M., Quinn, A. K., … Mujtaba, M. (2015). Ghana randomized air pollution and health study (GRAPHS): study protocol for a randomized controlled trial. *Trials*, *16*, 1.

Jeuland, M., Pattanayak, S. K., & Bluffstone, R. (2015). The Economics of Household Air Pollution. *Annual Review of Resource Economics*, *7*(1), 81–108. https://doi.org/10.1146/annurev-resource-100814-125048

Jeuland, M., Pattanayak, S. K., Soo, T., & Sheng, J. (2014). *Preference Heterogeneity and Adoption of Environmental Health Improvements: Evidence from a Cookstove Promotion Experiment* (SSRN Scholarly Paper No. ID 2490530). Retrieved from Social Science Research Network website: https://papers.ssrn.com/abstract=2490530

Johnson, M. A., & Chiang, R. A. (2015). Quantitative stove use and ventilation guidance for behavior change strategies. *J Health Commun*, *20 Suppl 1*, 6–9. https://doi.org/10.1080/10810730.2014.994246

Lewis, J. J., & Pattanayak, S. K. (2012). Who adopts improved fuels and cookstoves? A systematic review. *Environmental Health Perspectives*, *120*(5), 637.

Lim, S. S., Vos, T., Flaxman, A. D., Danaei, G., Shibuya, K., Adair-Rohani, H., … Andrews, K. G. (2013). A comparative risk assessment of burden of disease and injury attributable to 67 risk factors and risk factor clusters in 21 regions, 1990–2010: a systematic analysis for the Global Burden of Disease Study 2010. *The Lancet*, *380*, 2224–2260.

Masera, O. R., Saatkamp, B. D., & Kammen, D. M. (2000). From linear fuel switching to multiple cooking strategies: a critique and alternative to the energy ladder model. *World Development*, *28*, 2083–2103.

Mortimer, K., Ndamala, C. B., Naunje, A. W., Malava, J., Katundu, C., Weston, W., … Nyirenda, M. (2017). A cleaner burning biomass-fuelled cookstove intervention to prevent pneumonia in children under 5 years old in rural Malawi (the Cooking and Pneumonia Study): a cluster randomised controlled trial. *The Lancet*, *389*(10065), 167–175.

Mosler, H.-J. (2012). A systematic approach to behavior change interventions for the water and sanitation sector in developing countries: a conceptual model, a review, and a guideline. *International Journal of Environmental Health Research*, *22*, 431–449.

Moulton, L. H. (2004). Covariate-based constrained randomization of group-randomized trials. *Clinical Trials*, *1*(3), 297–305.

NPA. (2017, October 15). Cylinder Re-circulation Module [Government]. Retrieved April 24, 2019, from Ghana National Petroleum Authority website: http://www.npa.gov.gh/news/cylinder-re-circulation-module

Owusu-Agyei, S., Ernest A. Nettey, O., Zandoh, C., Sulemana, A., Adda, R., Amenga-Etego, S., & Mbacke, C. (2012). Demographic patterns and trends in Central Ghana: baseline indicators from the Kintampo Health and Demographic Surveillance System. *Global Health Action*, *5*(1), 19033.

Piedrahita, R., Dickinson, K. L., Kanyomse, E., Coffey, E., Alirigia, R., Hagar, Y., … Hannigan, M. (2016). Assessment of cookstove stacking in Northern Ghana using surveys and stove use monitors. *Energy for Sustainable Development*, *34*, 67–76. https://doi.org/10.1016/j.esd.2016.07.007

Pope, D., Bruce, N., Dherani, M., Jagoe, K., & Rehfuess, E. (2017). Real-life effectiveness of 'improved'stoves and clean fuels in reducing PM 2.5 and CO: Systematic review and meta-analysis. *Environment International*, *101*, 7–18.

Puzzolo, E., Stanistreet, D., Pope, D., Bruce, N., & Rehfuess, E. (2013). *Factors influencing the large-scale uptake by households of cleaner and more efficient household energy technologies*. Retrieved from http://eppi.ioe.ac.uk/cms/LinkClick.aspx?fileticket=aj-ASjMq1wk%3d&tabid=3426

Rehfuess, E. A., Puzzolo, E., Stanistreet, D., Pope, D., & Bruce, N. G. (2014). Enablers and barriers to large-scale uptake of improved solid fuel stoves: a systematic review. *Environmental Health Perspectives*, *122*(2), 120–130. https://doi.org/10.1289/ehp.1306639

Ruark, A., Chase, R., Hembling, J., Davis, V. R., Perrin, P. C., & Brewster-Lee, D. (2017). Measuring couple relationship quality in a rural African population: Validation of a Couple Functionality Assessment Tool in Malawi. *PLOS ONE*, *12*(11), e0188561. https://doi.org/10.1371/journal.pone.0188561

Ruiz-Mercado, I., Canuz, E., & Smith, K. R. (2012). Temperature dataloggers as stove use monitors (SUMs): Field methods and signal analysis. *Biomass and Bioenergy*, *47*, 459–468.

Ruiz-Mercado, I., & Masera, O. (2015). Patterns of Stove Use in the Context of Fuel–Device Stacking: Rationale and Implications. *EcoHealth*, *12*(1), 42–56. https://doi.org/10.1007/s10393-015-1009-4

Ruiz-Mercado, I., Masera, O., Zamora, H., & Smith, K. R. (2011). Adoption and sustained use of improved cookstoves. *Energy Policy*, *39*(12), 7557–7566. https://doi.org/10.1016/j.enpol.2011.03.028

Smith, K. R., Bruce, N., Balakrishnan, K., Adair-Rohani, H., Balmes, J., Chafe, Z., … Hap Cra Risk Expert Group. (2014). Millions dead: how do we know and what does it mean? Methods used in the comparative risk assessment of household air pollution. *Annu Rev Public Health*, *35*, 185–206. https://doi.org/10.1146/annurev-publhealth-032013-182356

Smith, Kirk R., McCracken, J. P., Weber, M. W., Hubbard, A., Jenny, A., Thompson, L. M., … Bruce, N. (2011). Effect of reduction in household air pollution on childhood pneumonia in Guatemala (RESPIRE): a randomised controlled trial. *The Lancet*, *378*, 1717–1726.

Stanaway, J. D., Afshin, A., Gakidou, E., Lim, S. S., Abate, D., Abate, K. H., … Murray, C. J. L. (2018). Global, regional, and national comparative risk assessment of 84 behavioural, environmental and occupational, and metabolic risks or clusters of risks for 195 countries and territories, 1990–2017: a systematic analysis for the Global Burden of Disease Study 2017. *The Lancet*, *392*(10159), 1923–1994. https://doi.org/10.1016/S0140-6736(18)32225-6

Stanistreet, D., Hyseni, L., Bashin, M., Sadumah, I., Pope, D., Sage, M., & Bruce, N. (2015). The role of mixed methods in improved cookstove research. *J Health Commun*, *20 Suppl 1*, 84–93. https://doi.org/10.1080/10810730.2014.999896

Streets, D. G., Bond, T. C., Carmichael, G. R., Fernandes, S. D., Fu, Q., He, D., … Yarber, K. F. (2003). An inventory of gaseous and primary aerosol emissions in Asia in the year 2000. *Journal of Geophysical Research: Atmospheres*, *108*(D21), n/a-n/a. https://doi.org/10.1029/2002JD003093

Van Vliet, E. D., Asante, K., Jack, D. W., Kinney, P. L., Whyatt, R. M., Chillrud, S. N., … Owusu-Agyei, S. (2013). Personal exposures to fine particulate matter and black carbon in households cooking with biomass fuels in rural Ghana. *Environmental Research*, *127*, 40–48.

Wilson, D. L., Adam, M. I., Abbas, O., Coyle, J., Kirk, A., Rosa, J., & Gadgil, A. J. (2015). Comparing Cookstove Usage Measured with Sensors Versus Cell Phone-Based Surveys in Darfur, Sudan. In S. Hostettler, E. Hazboun, & J.-C. Bolay (Eds.), *Technologies for Development* (pp. 211–221). Springer International Publishing.

WLPGA. (2015). *Accelerating the LPG transition: Global Lessons from Innovative Business and Distribution Models*. Retrieved from https://www.wlpga.org/wp-content/uploads/2015/09/accelerating-the-lpg-transition-2015-light.pdf

Zhou, Z., Dionisio, K. L., Arku, R. E., Quaye, A., Hughes, A. F., Vallarino, J., … Ezzati, M. (2011). Household and community poverty, biomass use, and air pollution in Accra, Ghana. *Proceedings of the National Academy of Sciences*, *108*(27), 11028–11033.

Zhou, Z., Dionisio, K. L., Verissimo, T. G., Kerr, A. S., Coull, B., Howie, S., … Fornace, K. (2014). Chemical characterization and source apportionment of household fine particulate matter in rural, peri-urban, and urban West Africa. *Environmental Science & Technology*, *48*(2), 1343–1351.

CONCLUSION

The work presented in this dissertation adds to a growing body of literature on the health effects of HAP, and opportunities to intervene on exposure. Our findings have important implications for Ghanaian policy, but also the direction of future biomedical and public health research.

Key findings and implications: Chapter 1

The first chapter presents results from a study on the relationship between air pollution exposure and microbial presence in infant nasal cavities. In an ITT analysis, we found that infants in the 3-stone arm had a higher microbial species presence compared to those in LPG intervention arm. When we focused on the differences between bacterial and viral presence, we found that the differences were driven by increased bacterial species presence, and there were no differences in viral presence. Three bacteria *S.pneumoniae*, *M.catarrhalis*, and *H.influenzae* appeared more often among cases in the 3-stone arm compared to cases in the LPG arm. Although exposure-response relationships did not lead to the same conclusions, there is a suggestion that HAP may increase the odds of testing positive for one bacteria, regardless of species.

Results from this work have implications for research and medical interventions. These findings support the mounting evidence for the theory that HAP-associated LRI is of bacterial origin. Each study presenting this finding has resulted from different study designs and geographical regions, from Guatemala, Malawi, and most recently South Africa (Rylance et al., 2015, 2016; Smith et al., 2011; Vanker et al., 2019). The heterogeneity in approach and context but similarity of results is encouraging. Pinpointing microbial pathogens responsible for the burden of HAP-associated pneumonia incidence could lead to developments in treatment or immunizations. This would be particularly practical in Ghana, where vaccine access and uptake is high (GHS, 2015). More sensitive PCR methods would be required to identify if there are species sub-types that are pathogenic, and for which we do not yet have immunizations. This approach, however, assumes that there are specific, identifiable, microbial pathogens responsible for infection.

In Chapter 1, we discuss the limitation that MassTag PCR is a coarse metric, and that newer methods may be required to understand underlying microbial relationships, i.e. shotgun metagenomics or 16s ribosomal sequencing. Therefore, we imply that air pollution may be leading to microbiomal dysbiosis, a disruption of the homeostatic respiratory microbial ecology. If so, this presents two specific challenges. The first is that the work in Chapter 1 searches for a particular bacterium of interest. However, if true that damage to respiratory tissue disrupts established, or developing, niches, then subsequent microbial inhabitance may depend on which species are abundant in a particular geographic location or population. This leads to the second challenge, which is that the results of HAP and microbiome studies may be context-specific. Perhaps this is unsurprising given that most other microbiome studies are shown to vary by geography (Yatsunenko et al., 2012) and/or population (Mason, Nagaraja, Camerlengo, Joshi, & Kumar, 2013). For example, we mention that *S. pnuemoniae* and *H. influenzae* may be particularly high in West Africa (Adetifa et al., 2012; Goetghebuer et al., 2000; Hill et al., 2008). If those bacterial species inhabit and/or proliferate in disrupted niches during dysbiosis, then it may be true that other species would fill this niche in other parts of the world where these bacteria are less abundant (Gupta, Paul, & Dutta, 2017).

If the relationship between HAP and pneumonia is microbiomal in nature, this would require different therapeutic responses. Microbiomal treatments have been developed for the gut microbiome (Reardon, 2014), but to our knowledge, no such therapies have been developed for the respiratory system. Therefore, medical intervention would be a longer-term endeavor.

Key findings and implications: Chapters 2 and 3

In Chapter 2, we utilize the novel framework of suspended use to consider the impediments of sustained use and reasons for discontinuing use of intervention stoves. We find that LPG users use their stoves more than BioLite users while fuel is free, but less than BioLite when they have to pay for the fuel. LPG and BioLite stove users report challenges cooking traditional dishes on intervention stoves, and those who experience burns use the stoves less over time. BioLite users experience burns substantially more than LPG or 3-stone fire users. Many LPG users report not using their stoves because of reported stove breakage. Finally, we find that LPG users discontinue use sooner when they live further away from high tree canopy areas.

Our key findings from Chapter 3 show that a RANAS behavior change intervention increased knowledge and attitudes towards LPG, but only when delivered in a single intervention. In a dual intervention with direct delivery of LPG fuel, surprisingly the RANAS intervention had no effect on these behavioral factors. While the results of our analysis on sustained use was hindered by missing data, our combination of main results, imputed main results, and secondary results made us confident that sustained use did increase in all three intervention arms. The magnitude of the differences were small, amounting to 122 additional minutes of additional use over six months when compared to the control arm. These differences imply persistent stove stacking and are unlikely to have meaningfully lowered HAP exposures.

Together, Chapters 2 and 3 have important implications for household energy in Ghana. We see that, when LPG is free and accessible, people largely use it. When LPG was free to participants during GRAPHS, overall LPG stove use was approximately 80%. While this is high, this means that 20% were not using LPG. This implies that price is major element of fuel choice, but not the only one. Recent evidence from Ecuador has shown persistent stove stacking even in the context of heavily subsidized LPG fuel (Gould et al., 2018). This is an important consideration, as it implies that cost may not be a sufficient intervention to incentivize use, and that comprehensive interventions may be necessary to increase sustained use. Cheaper fuel is unlikely to change people's perceptions of cultural suitability, experience with burns, or ability to address device breakage. Other research has found some individuals in Ghana fear that LPG is unsafe (Dalaba et al., 2018; WHO, 2018). This is unsurprising given recent LPG-related explosions in Ghana that were widely publicized and led to major policy reform (Asante et al., 2018). Therefore, we must consider policy scenarios that address energy poverty through affordability, accessibility, and other context-specific socioecological factors.

Energy policies in Ghana are already aimed towards a more sustainable energy mix, and recent LPG policy reforms may continue to move the country along that trajectory. Our findings have the opportunity to inform a rapidly developing energy infrastructure in Ghana. For example, currently Ghana has centralized refilling stations (Asante et al., 2018). Under the new LPG policies, individuals will no longer own their cylinders and will instead swap them out when refilling. If individuals no longer own their cylinders, then the pre-filled cylinders can potentially be sold in de-centralized, smaller commercial locations. This would increase accessibility of LPG, similar to our direct delivery intervention.

Our work also has ramifications for household energy research more broadly. The suspended use framework is a novel approach to considering the scale up of clean cooking fuels. Researchers have widely documented high initial use of new cooking technologies, but decreasing and/or discontinued use over time (Hanna, Duflo, & Greenstone, 2012). Most studies have employed the sustained use framework, which focuses on the enablers and barriers of continued stove use over time (Puzzolo, Pope, Stanistreet, Rehfuess, & Bruce, 2016; Rehfuess, Puzzolo, Stanistreet, Pope, & Bruce, 2014). In reality, the suspended use framework is simply flips that perspective, and may often call for the same analytical methods. In our case, however, it prompted novel uses of text mining and survival analysis methods that were not originally part of our analysis plan. Therefore, this change in perspective may be useful for researchers and policymakers when considering household energy interventions.

The ELAG study offers vital insights into potential interventions to increase the sustained use of clean cookstoves. We find that behavioral interventions *can* increase sustained use, and our imputed findings support that direct delivery can also increase use. Nevertheless, there is an important caveat, which is that this is a prime example of the difference between statistical and practical significance. While the findings of these interventions were statistically significant, the increases were marginal. Ultimately, our goal is to reduce overall biomass combustion and subsequent exposures to HAP. We did not measure personal exposure in ELAG, but it is unlikely that the marginal increases in LPG use resulted in meaningful, or any, exposure reductions.

In order to appreciate health benefits from cooking interventions, we must increase sustained use such that biomass combustion decreases. Our work supports the notion that no one factor is sufficient to increase sustained use of clean cookstoves. This may be relatively intuitive, but studies to date have mostly focused on specific interventions in isolation. Our work represents a stride in the right direction, by providing free stoves and a factorial trial to test the potential benefits of a dual intervention. But we demonstrate that even more is needed. A trial currently underway in rural areas of four countries is testing the potential benefits of community-scale interventions, by providing free stoves, LPG fuel, direct delivery, and behavioral interventions (Clasen, 2016). Preliminary results suggest that this cookstove intervention trial may be able to decrease $PM_{2.5}$ exposures to the WHO interim target guidelines (Johnson et al., 2018).

Directions for future research

Future research between HAP and LRI etiology can focus on two factors. One follows the theory that specific microbial pathogens are responsible for HAP-associated pneumonia. If so, then future research should employ PCR methods with a larger library of microbes. The specific goal of this research would not only be to identify other microbes of interest, but also serotyping. This is particularly important given that vaccine development is serotype-specific, relying on training immune cells on specific antigen recognition. The second potential relationship is that HAP causes dysbiosis of the respiratory tract ecology, which allows for pathogenic colonization and altered microbiomal composition. If so, then shotgun metagenomics or 16s ribosomal sequencing would be required to identify the presence and abundance of all microbiomal inhabitants. To our knowledge, no work has established the baseline conditions of the respiratory microbiome in Ghana. This would be a valuable first step to then understanding changes under varying levels of air pollution exposure.

Research on sustained and suspended use in Ghana has multiple outstanding research questions. To our knowledge, no one has yet published on the willingness-to-pay (WTP) for LPG fuels in Ghana. However, we do know of ongoing in northern Ghana demonstrating a high WTP for clean or improved cookstoves, above market rates, but a WTP for LPG fuel that is substantially below market rates (Dickinson et al., 2018). Future research should identify the WTP, but also price as a determinant of sustained use, in isolation or in combination with other interventions.

Future sustained use studies should also track traditional stove use in addition to the intervention stoves. We intended to do this in the Chapter 2 and 3 studies, but were unsuccessful due to logistical constraints. While we are interested in increasing clean cookstove use, HAP reductions are only possible if it displaces traditional cookstove use. It is rarely financially feasible to perform an intervention and simultaneously track stove use and personal exposures. Therefore, when interventions prove fruitful in decreasing biomass combustion, personal exposure can be monitored to identify differences in HAP.

The ELAG trial developed a rich dataset that can be the basis of several other research studies. We reported on the main experimental outcomes of the study, but there is an opportunity for adjusted analysis of stove use. A wide array of covariates were collected throughout the study period, including participant income, expenditures, adverse life events, the price of LPG, and household gender dynamics.

Stove use can be modeled as a function of these covariates. We also note that RANAS behavioral intervention was effective in one arm, but not in the dual intervention arm. Process evaluation data was collected that may allow us to understand observed differences. These analyses would interrogate whether there were meaningful differences in how the interventions were delivered or received. Ultimately, these would help us understand the viability of the RANAS model as a tool among household energy and access interventions.

Finally, the Ghanaian government is actively promoting public health initiatives and sustainable energy policies. These activities are ripe for policy evaluation tools like health impact assessments and health impact evaluation. Health impact assessments allow us to look prospectively to estimate the potential effects of various policy scenarios, providing an evidence base to weigh projected costs and health benefits. If we identify successful interventions to increase sustained use, the cost of scale up can be quantified and weighed against the projected benefits via health impact analyses. On the other hand, impact evaluation methods allow us to look retrospectively to estimate the causal effect of an enacted policy intervention. Both scenarios have the potential to support Ghana on its trajectory to improve public health for citizens nationwide.

References

Adetifa, I. M. O., Antonio, M., Okoromah, C. A. N., Ebruke, C., Inem, V., Nsekpong, D., … Adegbola, R. A. (2012). Pre-Vaccination Nasopharyngeal Pneumococcal Carriage in a Nigerian Population: Epidemiology and Population Biology. *PLoS ONE*, *7*(1). https://doi.org/10.1371/journal.pone.0030548

Asante, K. P., Afari-Asiedu, S., Abdulai, M. A., Dalaba, M. A., Carrión, D., Dickinson, K. L., … Jack, D. W. (2018). Ghana's rural liquefied petroleum gas program scale up: A case study. *Energy for Sustainable Development*, *46*, 94–102. https://doi.org/10.1016/j.esd.2018.06.010

Clasen, T. (2016). Household Air Pollution and Health: A Multi-country LPG Intervention Trial. Retrieved May 20, 2019, from https://clinicaltrials.gov/ct2/show/NCT02944682

Dalaba, M., Alirigia, R., Mesenbring, E., Coffey, E., Brown, Z., Hannigan, M., … Dickinson, K. L. (2018). Liquified Petroleum Gas (LPG) Supply and Demand for Cooking in Northern Ghana. *EcoHealth*, *15*(4), 716–728. https://doi.org/10.1007/s10393-018-1351-4

Dickinson, K. L., Dalaba, M., Brown, Z. S., Alirigia, R., Coffey, E. R., Mesenbring, E., … Hannigan, M. P. (2018). Prices, peers, and perceptions (P3): study protocol for improved biomass cookstove project in northern Ghana. *BMC Public Health*, *18*(1), 1209. https://doi.org/10.1186/s12889-018-6116-z

GHS. (2015). *The Health Sector in Ghana: Facts and Figures*. Retrieved from Ghana Health Service website: http://www.moh.gov.gh/wp-content/uploads/2017/07/Facts-and-figures-2015.pdf

Goetghebuer, T., West, T. E., Wermenbol, V., Cadbury, A. L., Milligan, P., Lloyd-Evans, N., … Weber, M. W. (2000). Outcome of meningitis caused by Streptococcus pneumoniae and Haemophilus influenzae type b in children in The Gambia. *Tropical Medicine & International Health*, *5*(3), 207–213.

Gould, C. F., Schlesinger, S., Toasa, A. O., Thurber, M., Waters, W. F., Graham, J. P., & Jack, D. W. (2018). Government policy, clean fuel access, and persistent fuel stacking in Ecuador. *Energy for Sustainable Development*, *46*, 111–122. https://doi.org/10.1016/j.esd.2018.05.009

Gupta, V. K., Paul, S., & Dutta, C. (2017). Geography, Ethnicity or Subsistence-Specific Variations in Human Microbiome Composition and Diversity. *Frontiers in Microbiology*, *8*, 1162. https://doi.org/10.3389/fmicb.2017.01162

Hanna, R., Duflo, E., & Greenstone, M. (2012). *Up in Smoke: The Influence of Household Behavior on the Long-Run Impact of Improved Cooking Stoves* (No. w18033; p. w18033). https://doi.org/10.3386/w18033

Hill, P. C., Cheung, Y. B., Akisanya, A., Sankareh, K., Lahai, G., Greenwood, B. M., & Adegbola, R. A. (2008). Nasopharyngeal Carriage of Streptococcus pneumoniae in Gambian Infants: A Longitudinal Study. *Clinical Infectious Diseases*, *46*(6), 807–814. https://doi.org/10.1086/528688

Johnson, M., Piedrahita, R., Garland, C., Pillarisetti, A., Sambandam, S., Gurusamy, T., … Clasen, T. (2018). Exposures to PM2.5 Associated with LPG Stove and Fuel Interventions in Four Countries: Pilot Results from the HAPIN Trial. *ISEE Conference Abstracts*. Retrieved from https://ehp.niehs.nih.gov/doi/10.1289/isesisee.2018.O02.03.31

Mason, M. R., Nagaraja, H. N., Camerlengo, T., Joshi, V., & Kumar, P. S. (2013). Deep sequencing identifies ethnicity-specific bacterial signatures in the oral microbiome. *PloS One*, *8*(10), e77287.

Puzzolo, E., Pope, D., Stanistreet, D., Rehfuess, E. A., & Bruce, N. G. (2016). Clean fuels for resource-poor settings: A systematic review of barriers and enablers to adoption and sustained use. *Environmental Research*, *146*, 218–234. https://doi.org/10.1016/j.envres.2016.01.002

Reardon, S. (2014). Microbiome therapy gains market traction. *Nature News*, *509*(7500), 269.

Rehfuess, E. A., Puzzolo, E., Stanistreet, D., Pope, D., & Bruce, N. G. (2014). Enablers and Barriers to Large-Scale Uptake of Improved Solid Fuel Stoves: A Systematic Review. *Environmental Health Perspectives*, *122*(2), 120–130. https://doi.org/10.1289/ehp.1306639

Rylance, J., Chimpini, C., Semple, S., Russell, D. G., Jackson, M. J., Heyderman, R. S., & Gordon, S. B. (2015). Chronic Household Air Pollution Exposure Is Associated with Impaired Alveolar Macrophage Function in Malawian Non-Smokers. *PLOS ONE*, *10*(9), e0138762. https://doi.org/10.1371/journal.pone.0138762

Rylance, J., Kankwatira, A., Nelson, D. E., Toh, E., Day, R. B., Lin, H., … Gordon, S. B. (2016). Household air pollution and the lung microbiome of healthy adults in Malawi: a cross-sectional study. *BMC Microbiology*, *16*(1). https://doi.org/10.1186/s12866-016-0803-7

Smith, K. R., McCracken, J. P., Weber, M. W., Hubbard, A., Jenny, A., Thompson, L. M., … Bruce, N. (2011). Effect of reduction in household air pollution on childhood pneumonia in Guatemala (RESPIRE): a randomised controlled trial. *The Lancet*, *378*(9804), 1717–1726. https://doi.org/10.1016/S0140-6736(11)60921-5

Vanker, A., Nduru, P. M., Barnett, W., Dube, F. S., Sly, P. D., Gie, R. P., … Zar, H. J. (2019). Indoor air pollution and tobacco smoke exposure: impact on nasopharyngeal bacterial carriage in mothers and infants in an African birth cohort study. *ERJ Open Research*, *5*(1), 00052–02018. https://doi.org/10.1183/23120541.00052-2018

WHO. (2018). *Opportunities for transition to clean household energy: application of the Household Energy Assessment Rapid Tool (HEART) in Ghana*. Retrieved from https://www.who.int/airpollution/publications/transition-to-clean-household-energy-Ghana/en/

Yatsunenko, T., Rey, F. E., Manary, M. J., Trehan, I., Dominguez-Bello, M. G., Contreras, M., … Anokhin, A. P. (2012). Human gut microbiome viewed across age and geography. *Nature*, *486*(7402), 222.